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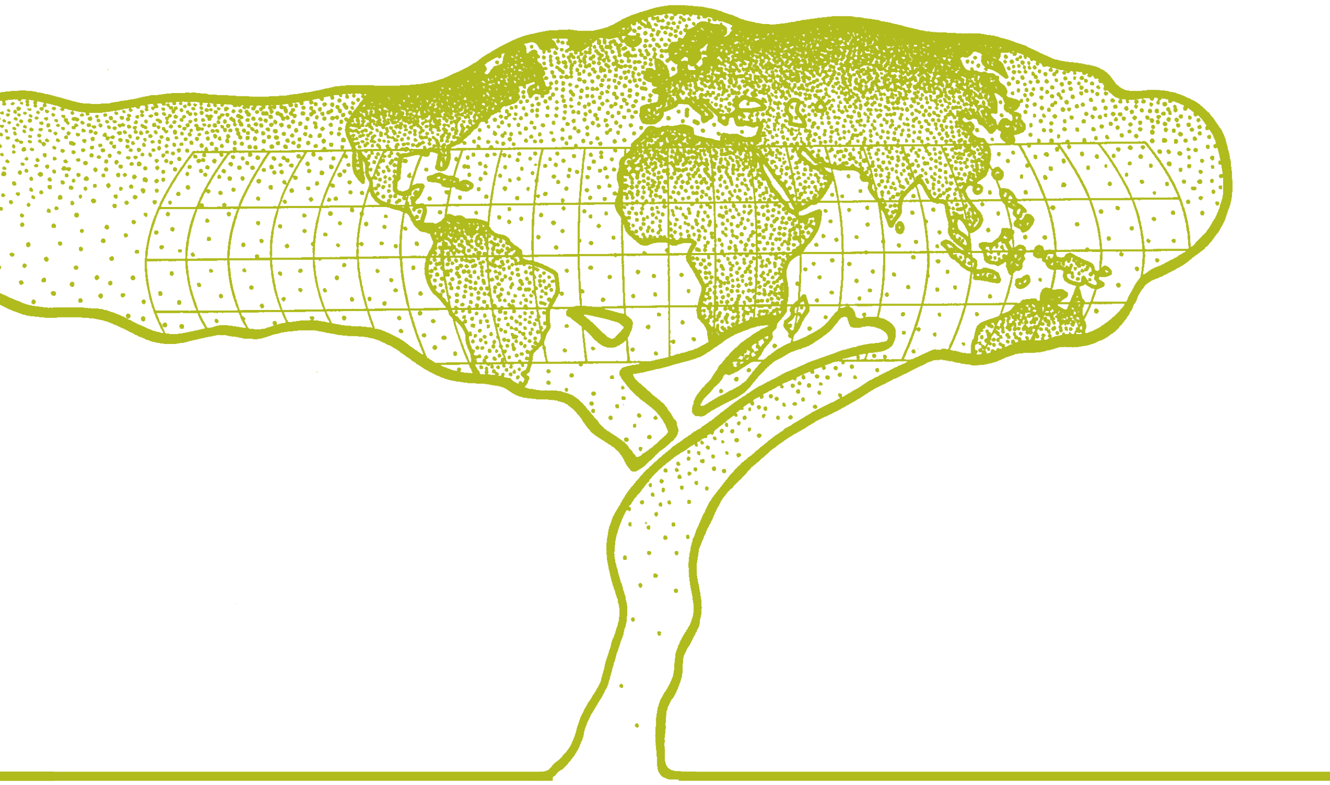

Raúl CORDOVA

Climate change adaptation in smallholder agroforestry systems in the Northern Andes of Ecuador: A case study in the Indigenous Territory of Kayambi People

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Climate change adaptation in smallholder agroforestry systems in the Northern Andes of Ecuador: A case study in the Indigenous Territory of Kayambi People

Raúl CORDOVA

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ABSTRACT

Smallholder farming is important in global agricultural production, food supply/security, sustainable biodiversity management and land use change processes. This sector is recognised as being highly vulnerable to climate change and climatic variability, especially in mountainous regions of the developing world, mainly due to high environmental exposure and sensitivity, and low adaptive capacity to a variety of climate and non-climate stressors. This high vulnerability of smallholder farming systems affects their biophysical and socioeconomic components, influencing the systems' functionality and farmers' livelihoods. Therefore, the maintenance of more sustainable and resilient agricultural systems constitute essential aspects to guarantee the sustainable management of land and assure millions of rural and urban livelihoods. However, scientific studies on this topic are lacking. In this context the aim of this study was to evaluate the main socioeconomic and environmental parameters which influence the adaptation of smallholder farmers and their farming systems to the impacts of climate change and climatic variability.

The adaptation opportunities and constraints of smallholder farmers and their systems were determined comparing their biophysical and socioeconomic sustainability (Study I), and their vulnerability to climate change and climatic variability (Study II and Study III). Sustainability and vulnerability analysis were conducted using primary data collected during 2015–2016. The dataset included a variety of socioeconomic and environmental parameters collected through 60 household interviews, including 30 farmers of agroforestry systems and 30 farmers of conventional agriculture systems. All the interviews were conducted in the Indigenous Territory of Kayambi People, located in the Northern Andes of Ecuador, and represent mainly the perceptions of Kayambi farmers about how climate and climate-related stressors affect the sustainability and vulnerability of their farming systems and livelihoods.

Semi-structured questionnaires were designed to collect primary biophysical, socioeconomic and sustainability data, while a modified Climate Change Questionnaire Version 2 of the World Overview of Conservation Approaches and Technologies (WOCAT) was used to collect the vulnerability data. The different characteristics of the farming system types were analysed applying a comparative analysis approach. Qualitative variables were analysed through descriptive statistics (Crosstabs and Chi-square), while inferential statistical tests (Independent Samples t Tests) were applied for the quantitative variables.

The main findings highlight the role of agroforestry systems in maintaining and enhancing the sustainability of the systems and farmers' livelihoods; with agroforesters perceiving higher levels of agrobiodiversity, greater diversification of livelihoods, more secured land tenure, better on-farm incomes, greater variety and diversification of irrigation sources, and less dependence on rainfed agriculture compared to conventional farmers.

The results also indicate that agroforestry systems are less vulnerable and more resilient to the impacts of climate change and climatic variability. Farmers in both farming systems perceived similar temperature increases and decreased precipitation for both the past and projections for the next decade. Results also indicated that conventional systems had greater exposure to solar radiation; pests, weeds and disease outbreaks; and droughts compared to agroforestry systems. In contrast, agroforestry systems presented greater potential to decrease exposure and sensitivity, and greater assets to support the adaptive capacity of farmers, especially in aspects related to social environment, information and productive infrastructure access. These results support previous assumptions about the key role of agroforestry systems for climate change adaptation and mitigation, especially in developing countries.

Keywords: Andean smallholder agroforestry and conventional agricultural systems, socioeconomic and biophysical sustainability, exposure, sensitivity, adaptive capacity, traditional knowledge

ABSTRACT IN SPANISH

La agricultura a pequeña escala constituye un importante sector en la producción agrícola mundial, suministro de alimentos y seguridad alimentaria, manejo sostenible de la biodiversidad, influyendo a su vez los procesos de cambio de uso de la tierra. Es conocido que este sector es altamente vulnerable al cambio y variabilidad climática, especialmente en las regiones de montaña de países en vías de desarrollo, debido principalmente a su elevada exposición y sensibilidad ambiental, y baja capacidad adaptativa a un sinnúmero de factores climáticos y no climáticos. La alta vulnerabilidad de estos sistemas tiende a afectar sus componentes biofísicos y socioeconómicos, influyendo en su funcionalidad y medios de vida agrícolas. Por consiguiente, el mantenimiento de sistemas agrícolas sostenibles y resilientes constituye un requisito indispensable para garantizar el manejo sostenible de la tierra y los medios de vida de millones de hogares rurales y urbanos. A pesar de esto, estudios científicos en este campo son escasos. En este contexto, el objetivo central del presente estudio se enfocó en evaluar los principales parámetros socioeconómicos y ambientales que influyen en la adaptación de los pequeños agricultores y sus sistemas agrícolas, a los efectos del cambio y variabilidad del clima. Las oportunidades y limitaciones de adaptación de los pequeños agricultores y sistemas agrícolas se determinaron comparando su sostenibilidad biofísica y socioeconómica (Estudio I), y su vulnerabilidad al cambio y variabilidad del clima (Estudio II y Estudio III). El análisis de la sostenibilidad y vulnerabilidad se lo realizó mediante una diversidad de parámetros socioeconómicos y ambientales recopilados a través de 60 entrevistas a nivel de finca durante los años 2015-2016. Las entrevistas incluyeron 30 sistemas agroforestales y 30 sistemas agrícolas convencionales, repartidos a lo largo del Territorio Indígena del Pueblo Kayambi, ubicado en la sierra norte de los Andes del Ecuador. La mayoría de datos analizados representan las percepciones de los agricultores Kayambi acerca cómo el clima y otros factores relacionados con el mismo, afectan la sostenibilidad y vulnerabilidad de sus sistemas agrícolas y medios de vida. Para tal efecto diseñaron cuestionarios semiestructurados para recopilar información primaria relacionada con la sostenibilidad biofísica y socioeconómica, mientras que para la vulnerabilidad, se utilizó una versión modificada del cuestionario sobre cambio climático versión 2 del Panorama Mundial de Enfoques y Tecnologías de la Conservación (WOCAT, por sus siglas en inglés). El análisis de las diferentes características de los dos tipos de sistemas estudiados se lo realizó mediante el enfoque de análisis comparativo. Las variables cualitativas se analizaron mediante estadísticas descriptivas (Tablas cruzadas y Chi cuadrado), mientras que para las variables cuantitativas se aplicó una prueba estadística inferencial (Prueba de t para muestras independientes). Los principales resultados y conclusiones de este estudio enfatizan el papel de los sistemas agroforestales en el mantenimiento y fortalecimiento de la sostenibilidad de estos sistemas y los medios de vida de los agricultores, recalcando que : los agricultores agroforestales percibieron mejores niveles de agrobiodiversidad; mayor diversificación de medios de vida; mejor seguridad en la tenencia de la tierra; mejores ingresos económicos derivados de la finca; mayor diversificación de fuentes y de sistemas de riego; y menor dependencia a la agricultura de secano que los agricultores convencionales. Los resultados indican también que los sistemas agroforestales son menos vulnerables y más resilientes a los efectos del cambio y la variabilidad del clima, enfatizando que: tanto los agricultores agroforestales como los convencionales perciben de manera similar el aumento de la temperatura y la disminución de las precipitaciones, durante la última y futura década proyectada. Adicionalmente, los agricultores convencionales perciben mayor exposición de sus sistemas a la sequía; radiación solar; y brotes de plagas, hierbas y enfermedades. En contraste, los agricultores agroforestales perciben que sus sistemas presentan mayor potencial para disminuir la exposición y sensibilidad, mostrando además mejores recursos para fortalecer su capacidad adaptativa, especialmente en aspectos relacionados con un mejor entorno social, acceso a información e infraestructura productiva. Estos resultados respaldan el conocido papel que desempeñan los sistemas agroforestales en la adaptación y mitigación del cambio climático, especialmente en los países en desarrollo.

Palabras clave: Sistemas andinos agroforestales y convencionales a pequeña escala, sostenibilidad socioeconómica y biofísica, exposición, sensibilidad, capacidad adaptativa, conocimiento tradicional

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PREFACE

This long Ph.D. journey started in 2012 when the Ecuadorian Government at that time decided that one of the ways to promote the development of the country, in the medium and long term, was to invest in higher education of qualified professionals and academics in the country. The opportunity to be part of this process through being selected as a scholarship holder for doctoral studies, and my acceptance to one of the top one hundred universities in the world, were of paramount importance for my academic development.

There are many people and institutions to thank for their support in bringing my doctoral studies to its end with great joy and hope.

First of all, I want to express my deep gratitude to Professor Markku Kanninen, my main supervisor, who, from the very beginning, trusted and supported my proposals and gave me the opportunity and freedom to arrange and conduct my studies and research work on my own times and in my own ways. The guidance, academic and administrative support of professor Kanninen were crucial during the research process, including the field work, writing and publishing the manuscripts and this dissertation summary.

My deepest thanks to Dr Nicholas Hogarth, my second supervisor, for his important academic contribution to the process by commenting, reviewing and editing the manuscripts and the thesis summary.

I would like to thank the reviewers of this thesis, Dr Irmeli Mustalahti and Dr Bruno Locatelli for their valuable suggestions and comments, which improved the quality of this thesis.

I am grateful to all the teachers and colleagues at the University of Helsinki, the Faculty of Agriculture and Forestry, the Department of Forest Ecology and the Viikki Tropical Resources Institute (VITRI), for sharing their experience and for giving the guidance and support during my stay in Finland. A special thanks to Professor Emeritus Olavi Luukkanen who introduced me to the Finnish higher education system through the University of Helsinki, and for his support during my master's studies. These were important elements that undoubtedly contributed in my decision to continue my doctoral studies at the University of Helsinki.

I want to express my special thanks to the Ecuadorian people, the government, the National Secretariat of Higher Education, Science, Technology and Innovation (SENESCYT), and the National Institute for the Promotion of Human Talent (IFTH) for the four-year scholarship they provided to conduct my doctoral studies. I am also grateful for the extra economic support provided by the Faculty of Agriculture and Forestry, the Department of Forest Ecology and VITRI for my field work activities, my participation in international conferences and for the publishing of the manuscripts.

My gratitude also goes to all the Kayambi farmers, women and men who participated in the field work activities, sharing their time, experiences and knowledge as part of their struggle for survival in the high Andes. Special thanks to Agustin Cachipuendo, President of the Kayambi People's Organisation for his willingness and support to conduct the field activities in the Kayambi Territory. I would also like thank Myriam Inlago and Cristian Otavalo, the wonderful couple who facilitated the cultural pertinence and the logistics in contacting the farmers and who accompanied me during most of the interviews.

I would like to express my deep thanks to my wonderful nuclear family, my wife Anna Vohlonen and my daughter Tamia Córdova, for all their endless love, patience and encouragement during this special time in our lives, suffering and rejoicing with me at every step of this process.

Finally, I wish to express my deepest gratitude for the unconditional love to my extended

families in Ecuador and Finland, especially to my parents Raúl Córdova and Mercedes Castro, my siblings Pethya, Andrés and Cristian Córdova Castro and their families, my in-laws Ilkka, Leena, Maiju and Touko Vohlonen and the rest of the family in Finland.

This work is dedicated to all the Andean people struggling to adapt and survive in the midst of the climate change, and all those people who trusted me, especially my wife, daughter, parents and all the dear relatives and friends in Ecuador and Finland.

Quito, October 2020

Raúl Clemente Córdova Castro

LIST OF ORIGINAL PAPERS

This thesis is based on the following original articles:

I. Córdova, R., Hogarth, N. J. & Kanninen, M. 2018. Sustainability of Smallholder Livelihoods in the Ecuadorian Highlands: A Comparison of Agroforestry and Conventional Agriculture Systems in the Indigenous Territory of Kayambi People. *Land* **7**(2): 45. https://doi.org/10.3390/land7020045

II. Córdova, R., Hogarth, N. J. & Kanninen, M. 2019. "Mountain Farming Systems' Exposure and Sensitivity to Climate Change and Variability: Agroforestry and Conventional Agriculture Systems Compared in Ecuador's Indigenous Territory of Kayambi People." *Sustainability* **11**(9): 2623. https://doi.org/10.3390/su11092623

III. Córdova, R.; Hogarth, N. J. & Kanninen, M. Adaptive capacity to climate change and variability among highland smallholder agroforesters and conventional farmers of the Indigenous Territory of Kayambi People in Ecuador (Submitted).

In all studies (Study I – III) Raúl Córdova conceived the research idea, the methods for data collection and analysis, carried out the field activities, collected and analysed the data for each paper, and wrote the firsts draft manuscripts. In all studies Nicholas Hogarth and Markku Kanninen advised regarding the data analysis, and made suggestions and modifications to all manuscripts in several stages, including the methods, the scientific approach and language.

LIST OF MAIN ACRONYMS

AFS	Agroforestry Systems
AR5	IPCC Fifth Assessment Report
CAS	Conventional Agricultural Systems
CCA	Climate Change Adaptation Module of WOCAT
CCRS	Climatic and Climate-Related Stressors
CCV	Climate Change and Climatic Variability
CH_4	Methane
CO_2	Carbon dioxide
CRiSTAL	The Community-based Risk Screening Tool – Adaptation and Livelihoods
CS	Climatic Stressors
ECE	Extreme Climatic Events
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse gases
INAMHI	National Institute of Meteorology and Hydrology of Ecuador
ITKP	Indigenous Territory of Kayambi People
LA	Latin America
MEW	Minimum Ecuadorian Wage
N_2O	Nitrous oxide
OECD	Organisation for Economic Cooperation and Development
PWD	Pests, weeds and diseases
SAFA	Sustainability Assessment of Food and Agriculture systems
SLM	Sustainable Land Management
UNCCD	United Nations Convention to Combat Desertification
WCCQV2	WOCAT Climate Change Questionnaire Version 2
WOCAT	World Overview of Conservation Approaches and Technologies

TABLE OF CONTENTS

1. Introduction

1.1. Socioeconomic, environmental, and vulnerability aspects of the global smallholder farming sector

The global smallholder farming sector represents about three billion rural people living in the developing world, distributed across approximately 475 million small farm households (Rapsomanikis 2015) and 570 million farms (Lowder et al. 2016). This sector is characterised by being family-operated, with limited or no hired labour, farm size less than 10 ha, and using part of the production for family consumption (FAO 2012, Samberg et al. 2016). Smallholders - especially in the developing world - often live in poverty, with food insecurity, limited access to markets, services, and productive assets, and are subject to environmental degradation such as soil erosion, water, and biological deterioration (Morton 2007, Nyssen et al. 2009, Berdegué and Fuentealba 2011, Rapsomanikis 2015). Despite the socioeconomic limitations and environmental degradation (which particularly affect farmers living in harsh environments such as arid regions and highlands in developing countries), smallholder farming is still the most common form of agriculture in the world, having an important role in food production and supply, and in the economies at local, regional and global-levels (Rapsomanikis 2015, Lowder et al. 2016, Samberg et al. 2016, Vadjunec et al. 2016).

The smallholder farming sector utilises about 75% of the global agricultural land (Lowder et al. 2016), being also responsible for more than half of the food calories produced globally, having an important influence on more than half the production of some major food crops worldwide, such as rice, groundnuts, oil palm, cassava, millet, wheat, rye and potatoes (Samberg et al. 2016). Other authors are, however, more conservative, estimating that smallholders occupy only 24% of global agricultural land, and responsible for about 28-31% and 30-34% of the global crop production and food supply respectively (Ricciardi et al. 2018). Regardless of the specific numbers, the influence of smallholder farmers on global food production means that they play a key role in land use/land-cover change processes and agrobiodiversity conservation (Zimmerer et al. 2015, Vadjunec et al. 2016, Zimmerer and Vanek 2016, Zimmerer and de Haan 2017).

In the global change context, smallholder farmers are considered to be highly vulnerable to the impacts of climate change and variability (CCV), and extreme climate events (ECE). This is mainly due to their extensive dependency on agriculture, livestock and natural resources, combined with poverty, lower education levels, isolation, and a lack of supportive climate-related policies (Dasgupta et al. 2014, Roy et al. 2018, Mbow et al. 2019). The global agriculture sector, including smallholders, is being affected by the increases in global mean temperature, shifts in precipitation regimes, increased ECE (especially droughts and floods), stimulatory effects of rising carbon dioxide (CO_2), and the damaging effects of elevated tropospheric ozone (O_3) (Dasgupta et al. 2014, Porter et al. 2014, Settele et al. 2014, FAO et al. 2018, Mbow et al. 2019). These climatic stressors (CS) are affecting the yields of the main staple crops (wheat, rice, maize, potato, beans and soybean) and livestock, increasing water demands for human consumption and farming activities, and promoting the expansion of pests, weeds and diseases (PWD) (Morton 2007, Dasgupta et al. 2014, Porter et al. 2014). Moreover, subsistence and smallholder livelihood systems, especially in developing countries, are also impacted by multiple non-climate stressors such as the limited access to productive assets (water, land, markets, financial resources, technology, knowledge and information), inadequate governance, increasing migration, gender inequity, pollution, health deterioration, natural resources disputes and armed conflicts, higher incidence of vector disease transmission, etc., which could affect smallholder farmers' systems and the associated livelihoods (Easterling et al. 2007, Morton 2007, Ribot 2010, Roy et al. 2018, Mbow et al. 2019).

1.2. Sustainability and vulnerability features of smallholder farming systems in Latin America and Ecuadorian highlands

Sustainability and vulnerability characteristics in relation to CCV features are similar for smallholder farming systems in Latin America (LA) and Ecuador as compared to the sector worldwide, but there are also important differences. Land grabbing and the consequent consolidation of large landholdings in the hands of a few landlords and agribusiness companies are undoubtedly the most remarkable socioeconomic processes that differentiate LA to other regions of the world (Graeub et al. 2016, Lowder et al. 2016). About 82% of farms in LA are operated by smallholder farmers, which is in line with the global context, but these farmers occupy only 18% of the agricultural land. In that sense, LA could be considered as the second most unequal region in terms of agricultural land distribution, preceded only by Oceania (Graeub et al. 2016). The increasing processes of land grabbing and consolidation in LA (Borras et al. 2014, Costantino 2014) could reduce the access of smallholders to agricultural land, promoting the expansion of the agricultural frontier, and accelerating the fragmentation and overexploitation of the limited agricultural land and water resources (Baquero et al. 2014). The lifelong poverty and marginalisation of smallholder farmers' households in LA increases social inequity, limiting their access to the main assets for production such as land, water, technical and financial support, technology and information (De Ferranti 2004, Baquero et al. 2014). As in the global context, smallholders in LA support food production systems and regional economies (Michael et al. 2014). In this sense, some authors indicate that the smallholder farming sector in LA is composed of about 66 million people, approximately 10% of 634 million inhabitants of the region (United Nations et al. 2015), of which 40–55 million are considered as indigenous people, being responsible for most of the staple crops produced and consumed in the region, such as beans (77%), potatoes (61%), and maize (55%) (Altieri et al. 2012). In addition, a study carried out in six LA countries indicated that the smallholder sector is responsible for 77% of rural employment (Soto et al. 2007).

The smallholder farming sector in Ecuador is typical for the LA region. Land consolidation/grabbing and unequal distribution of agricultural land, water, and other resources for production undermine the sustainability of farmers' livelihoods (Brassel et al. 2008, Isch and Zapatta 2010, Carrión and Herrera 2012). Consolidation of agricultural lands and water resources represents a significant socioeconomic-environmental problem in the country. Although about 76% of Ecuadorian farmers are smallholders (with less than 10 ha of land), these farmers use only 12% of the agricultural land, with only 26% of their lands irrigated, having access only to 13% of the total irrigation volume. On the other hand, only 6% of farmers have large holdings (>50 ha), occupying 61% of the land with more possibilities to irrigate the majority of their lands (51%) (INEC 2000, Larrea 2008, Gaybor 2010, Carrión and Herrera 2012). The unequal distribution of land and water resources (seen as primary subsistence and productive assets) increases poverty and marginalisation, which are historic problems faced by smallholders in the country (Tamayo and Hidalgo 2008, Carrión and Herrera 2012). These inequities usually generate socioeconomic, cultural and environmental discrimination, as it is reflected in the links among highly fragmented agricultural lands, high poverty level areas and the presence of indigenous groups. In the case of Ecuador this situation is more evident in high mountains (Brassel et al. 2008, Isch and Zapatta 2010, Carrión and Herrera 2012). As in the global and LA cases, smallholder farmers in Ecuador also play an important role in the production and supply of local food for most of the rural and urban populations. Many publications include the figures from the last agricultural national census (INEC 2000) to emphasise that the majority of the staple food consumed in the country comes from smallholder producers (Soto et al. 2007, Tamayo and Hidalgo 2008, Oyarzun et al. 2013, Borras et al. 2014, Michael et al. 2014, Salcedo et al. 2014), showing the importance of this sector in the maintenance of food security, sovereignty and agrobiodiversity. Despite the lack of specialised data on how the smallholder farming sector contributes to the national economy, some authors report that the agriculture sector contributes 9% to GDP, which represents about the 15% of the non-oil GDP, and provides direct employment to approximately 70% of the rural population (Carrión and Herrera 2012, Guerrero and Salvador 2015). Other authors discuss the influence of the smallholding sector in the permanent and non-permanent employment of the country's hired labour (16% and 40% respectively) (Guerrero and Salvador 2015). Taking into consideration that smallholder farming uses mainly unpaid family labour, these figures indicate the representative contribution of the smallholder sector supporting rural employment and livelihoods in Ecuador.

In terms of the vulnerability of smallholder farmers to CCV in LA, and especially in the case of the Tropical Andes, the impacts and projections follow similar global patterns described in section 1.1[1], although some regions are projected be exposed to the most dramatic climatic changes in LA (Urrutia and Vuille 2009, Magrin et al. 2014, Schoolmeester et al. 2016). Tropical highland landscapes are vulnerable to glacier retreat processes, due mainly to increases in temperature and changes in precipitation patterns in mountains. This is an extensively documented phenomenon which affects the water supply of millions of rural and urban users, with impacts also on agriculture and ecosystem functioning (Urrutia and Vuille 2009, Magrin et al. 2014, Reyer et al. 2017, Schoolmeester et al. 2016). Smallholder farming systems and livelihoods in the Tropical Andes are especially vulnerable due to their low adaptive capacity, characterised by high socioeconomic, environmental, and institutional marginalisation (high poverty, low access to water, land, information, technology, financial resources, training/education, and increasing degradation of natural resources such as water, soil and biodiversity) (Postigo et al. 2012, Sietz et al. 2012, Dasgupta et al. 2014). Among the expected impacts of CCV and ECE in Andean farming systems, the reductions in productivity of major crops and farm animals (mostly beef, dairy cattle, pigs and chickens), and the risk of PWD outbreaks that affect crops, animals and people, could be seen as the most representative ones (Urrutia and Vuille 2009, Anderson et al. 2011, Postigo et al. 2012, Porter et al. 2014, Reyer et al. 2017). On the other hand, Andean smallholder farmers, particularly in the case of indigenous people, have been developing over centuries a variety of coping strategies[2] to adapt to new socioeconomic and environmental conditions (von Wymann et al. 2013), which in the context of global change, could reduce their exposure, sensitivity and enhance their adaptive capacity and resilience (Easterling et al. 2007, Dasgupta et al. 2014, Córdova et al. 2018, Córdova et al. 2019).

1.3. Smallholder agroforestry systems for sustainable livelihoods and climate change adaptation/mitigation

Agroforestry (a diversified set of agricultural production systems that integrate trees with annual crop cultivation, livestock production, and other farm activities) is a land use and management approach implemented by about 1.2 billion people around the world, especially in tropical and developing

[1] Temperature increase, changes in precipitation regimes and increased frequency of extreme events.

[2] Highly biodiverse farming systems, diversified agricultural and natural resource management practices, well established local organisations/institutions for risk-sharing and management, site-specific knowledge.

countries (Jamnadass et al. 2013, Zomer et al. 2016). There is an extensive body of literature documenting the variety of socioeconomic and environmental benefits of agroforestry practices and systems to support sustainable farming systems, livelihoods, food and nutritional security, health, income, and their potential for climate change mitigation and adaptation (Franzel 2005, Swallow and Ochola 2006, Verchot et al. 2007, Zomer et al. 2014b, Zomer et al. 2016, Loboguerrero et al. 2019, Quandt et al. 2019).

In the global change context, the socioeconomic and environmental opportunities provided by agroforestry systems (AFS) to support the resilience and adaptive capacity of farmers' livelihoods could be considered superior compared with other land use systems at global, regional, watershed, and farm levels due to the optimisation of tradeoffs between increased food production, poverty alleviation, and environmental conservation (Sampson and Scholes 2000). These systems can reduce wind and water erosion, increase soil health and the availability of nutrients, are less prone to drought, provide watershed protection and support biodiversity (Young 1985, Thrupp 2004, Boelee 2011, Balvanera et al. 2016, Barrios et al. 2018). Agroforestry systems could also play an important role mitigating the emissions of greenhouse gases (GHGs), reducing the emissions of CO_2 and nitrous oxide (N_2O) from soils and increasing methane sinks (CH_4) strength compared with annual cropping systems (Lin 2014). Sampson and Scholes (2000), found that agroforestry presented the highest potential for carbon sequestration in non-Annex I countries[3], mainly due to the large area available for land use change (630 x 10^6 ha). These authors suggest that in general, agroforestry systems and practices could sequester carbon at time-averaged rates of 0.2-3.1 t C ha^{-1}, while in temperate areas[4] with agroforestry the potential carbon storage range was 15 to 198 t C ha^{-1}, with a modal value of 34 t C ha^{-1}. More recent studies also reported the mitigation potential across all agricultural pathways, including agroecological practices such as agroforestry (Zomer et al. 2016, Dooley et al. 2018b). In that sense, from the 8.54 Gigatons of CO_2 equivalent that could be mitigated globally per year and by 2050, about 12% (1.04 Gt CO_2eq) will represent the contributions of agroforestry practices as sequestered carbon, while the other 88% (7.5 Gt CO_2eq) will be the avoided emissions as a result of improved production (especially for livestock), less consumption (especially meat and dairy), and reduced waste of food and agricultural products (Dooley et al. 2018b). The value of carbon sequestered by agroforestry (as indicated above) could be seen as a conservative estimate because this value only takes into account above-ground carbon, without considering agroforestry's significant soil carbon component as compared with conventional agriculture systems (Dooley et al. 2018a). In addition, Dooley et al. (2108a) remark that the potential of agroforestry to sequester carbon could still be higher because only 300 Mha of permanent cropland were considered in the calculations, from the about 2,220 Mha classed as agricultural land (Zomer et al. 2016), of which 40% have been identified as being suitable for agroforestry (Dooley et al. 2018a).

[3] The countries under the Kyoto Protocol that not have legally binding emissions reductions targets. Most of them are developing countries located in tropics.

[4] Which could present similar conditions as in the high Andes.

1.4. Agroforestry systems in the highlands of Ecuador

Agroforestry in Ecuador has been practiced in all regions, especially in the Amazon and coastal areas where the indigenous peoples[5] still maintain their traditional production systems called *chakra* or *aja*[6].

In the case of the high Andes, the traditional agroforestry systems have been severely depleted as a result of colonisation, which influenced the production approach. The indigenous people of the Andes practiced traditional agroforestry for millennia, apparently without affecting the natural ecosystems. However, in some areas, and due to the intensification of agriculture and the lack of firewood, trees have disappeared progressively from the systems. Some examples of the traditional agroforestry practices in the Andean valleys are the live fences around the *chakra* and planting trees or shrubs along former sideways (Hofstede et al. 1998). Although most of the traditional agroforestry practices are not well documented, the current practices implemented in the high Andes could be seen as a variation of the following practices: contour-planted belts of trees/shrubs as living barriers, windbreak belts, trees in borders as living fences, silvopasture, on-farm copses, and fruit trees on farms (Hofstede et al. 1998).

In the past decades, the reforestation approach in the Ecuadorian highlands changed from massive bilateral contracts and industrial plantations to reforestation of the smallholding properties commonly situated in the hillsides, with the priorities being soil conservation, improvement of agricultural production through frost and wind protection, and improving the availability of timber products. In general, the preferred tree species in Ecuadorian highlands were the exotic and fast growing species such as pine (*Pinus radiata* and *Pinus patula*), cypress (*Cupressus macrocarpa* and *Cupressus lusitanica*) and eucalyptus (*Eucalyptus globulus* and *Eucalyptus saligna*), due also to their high yields and straight trunks. These species are commonly used as windbreak belts or trees in borders (Hofstede et al. 1998, Heerma van Voss et al. 2001). The popularity of these exotic species has declined in the last decades, mainly due to the environmental impacts on the hydrology, native vegetation, soil organic matter and in the physical and chemical properties of soil, especially in highland Andean grasslands (*Páramo*)[7] (Hofstede et al. 1998). Exotic tree species are known for their high water consumption and allelopathic effects, in particular for eucalyptus species. There are also many native species that are used for agroforestry instead of the exotic ones. For example, the Aliso (*Alnus acuminata*) is the most promoted species in the high Andes due to its nitrogen fixing properties, medicinal applications, firewood and timber supply, and for watershed management and protection activities. Other native species used are *Polylepis incana, Polylepis sericea* and *Polylepis racemosa* as windbreak belts, living fences and in silvopasture systems; *Buddleja spp.* in silvopasture systems and copses especially in hillsides; *Prunus serotina var capuli* in smallholding orchards; *Schinus molle* in windbreak belts and smallholding orchards; *Escalonia spp.* in windbreak belts and contour-planted belts; *Eritrina edullis* and *Eritrina poeppigiana* in living fences (Borja et al. 1992, Hofstede et al. 1998, Heerma van Voss et al. 2001).

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[5] Kichwa, Shuar, Achuar, Cofan and Secoya in the Amazon, and Chachi, Epera, Awa and Tsachila in the coast.

[6] Traditional rotating agroforestry system using multipurpose trees, and managed mainly by women to produce annual crops, medicinal plants, fruits, small scale livestock and minor animals.

[7] High mountain ecosystem similar to alpine tundra located mainly in the Andes of Colombia, Ecuador, and Peru.

In an assessment[8] conducted in four highland provinces of Ecuador (Imbabura, Pichincha, Cotopaxi and Chimborazo) as a scoping exercise to define the study area of this study, highland agroforestry systems were characterised by the following features:

- High agrobiodiversity levels (number of species, cultivars and breeds under the control and management of the farmer) and associated biodiversity (number of species of wild plants and animals usually found in the farm).
- Usage of a variety of multipurpose tree/shrubs species (firewood, timber, food-fruits, medicine, forage, boundary and on-farm delimitation, aesthetic), in different spatial arrangements (living fences for on- and off- farm zoning and delimitation). These tree/shrub species usually fulfil important socioeconomic and environmental functions supporting farmers' livelihoods and basic ecosystem services (moisture regulation and conservation, creating microclimates, control of wind and water erosion, shelter for wildlife, promotion of biodiversity, control of pests, weeds and diseases (PWD), maintenance of food security/sovereignty, income generation, etc.).
- The management approach to control PWD and soil fertility is based on agroecological principles, with low or no application of synthetic fertilisers and agrochemicals. Soil fertility is conserved and improved by adding self-produced organic fertilisers (compost, humus, manure, bokashi, biol[9], etc.), natural nitrogen fixation through N-fixing species (commonly legumes - beans, peas, lentils, broad beans, lupinus, vicia- and other *Fabaceae* trees/shrubs - *Inga spp.*, *Tecoma stands*, *Acasia spp.*, *Mimosa spp.*, *Caesalpinea spinosa*, *Cajanus cajan*- and others such as *Alnus acuminata* and *Casuarina equisetifolia*. The prevention and control of PWD are achieved by use of self-prepared biocides based on plants (*Brugmansia spp*., *Capsicum spp*., *Lupinus spp*., *Ambrosia arborescens*, onion, garlic, etc.). Additionally, the harvest and application of microorganisms in broths and biols, constitute complementary practices to improve the microbial activity in soil and thereby increasing the fertility and productivity.
- In most of the cases, the production is for family consumption, and depending on the accessibility of markets, some part of the production may be sold in local markets, representing an important economic income for the household. The production includes diversified traditional crops (many cultivars of maize, beans, broad beans, peas, lupinus, quinoa, tubers and roots -potatoes/*Solanum tuberosum*, oca/*Oxalis tuberosa*, mashwa/*Tropaeolum tuberosum*, miso/*Mirabilis expansa*, jicama/ *Smallanthus sonchifolius*, sweet potato/ *Ipomoea batatas*, melloco/*Ullucus tuberosus*, achira/*Canna indica*-), fruits (berries/*Rubus spp.*, chilguacán/*Vasconcella sp.*, chamburo/*Vasconcella sp.*, golden berry/*Physalis peruviana*, mountain black cherry/*Prunus serotina*, tree tomato/*Solanum betaceum*, banana passionfruit/*Passiflora spp*., sweet granadilla/*Passiflora ligularis*, guaba/*Inga spp.*), vegetables, medicinal and condiment plants, pastures, small scale livestock (cattle, sheep, goats, llamas and alpacas) and minor animals (guinea pigs, rabbits, pigs, chickens, turkeys, ducks, quails and gees).
- Due to high rates of rural to urban migration, especially men and youth (men and women), the highland production systems are in general managed and run by women. Women farmers tend

[8] Consisting of 15 socioeconomic and biophysical field interviews with smallholder agroforesters (unpublished).
[9] A liquid, organic fertiliser commonly used in organic and ecological agriculture.

to be organised in social networks for mutual support and better resilience (associations for production and commercialisation of agroecological and dairy products, community-based savings banks).

1.5. Study aims and hypothesis

The aim of this research was to provide socioeconomic and environmental data to evaluate factors influencing sustainability and vulnerability of smallholder farming systems to impacts of climate change and variability (CCV) in the Indigenous Territory of Kayambi People (ITKP), located in the Andean Highlands of Northern Ecuador. The studied farming systems were agroforestry systems (AFS) and conventional agricultural systems (CAS).

The main research question of this study was:

How sustainable and vulnerable are the farming systems in the ITKP to support the adaptation of smallholder farmers to climate change and variability?

While the specific research questions were:

1) What are the main socioeconomic and biophysical characteristics and differences between AFS and CAS? (Study I)
2) How do the AFS and CAS contribute to the socioeconomic and biophysical sustainability of smallholder farmers' livelihoods? (Study I)
3) Which of the two production systems provide better socioeconomic and biophysical opportunities to enhance the sustainability of smallholder farmers' livelihoods? (Study I)
4) What are the characteristics of exposure of the studied AFS and CAS to the impacts of CCV? (Study II)
5) How sensitive are the AFS and CAS to the impacts of CCV? (Study II)
6) What are the elements of adaptive capacity of the AFS and CAS? (Study III)

The hypotheses were:

1) The sustainability of AFS and CAS is influenced by the key socioeconomic and biophysical factors such as diversity and use of agroecosystems; soil fertility and microclimate conditions; livelihood diversification; on and off-farm income levels, land tenure, water availability, and characteristics of the irrigation system (Study I)
2) The vulnerability of the studied AFS and CAS to impacts of climate change and variability depends on the degree of exposure and sensitivity of the system in question, and on the adaptive capacity of farmers' livelihoods (Study II and III)

The three papers included in this study provide a comprehensive qualitative and quantitative analysis to broaden understanding of the interactions and complementarities of different socioeconomic and biophysical factors affecting the sustainability and vulnerability of smallholder farming systems in the Ecuadorian highlands. The comparative and multidisciplinary approach applied in this study allow a proper analysis and understanding of the advantages and constraints faced by agroforesters and conventional farmers to cope and deal with CCV.

2. Theoretical framework

The framework of this study was based on the literature associated with the socioeconomic and environmental factors influencing the adaptation and resilience of smallholder farming systems to CCV. Furthermore, the framework also takes into account the literature related to the main biophysical and socioeconomic factors supporting or affecting the sustainability of the farming systems, and on approaches used to analyse the vulnerability of smallholder farming systems to CCV (based on concepts of exposure, sensitivity and adaptive capacity) (Figure 1).

2.1. Main biophysical and socioeconomic factors influencing the sustainability in farming systems

Sustainability measurement in farming systems tends to be a complex process without a uniform point of view among academics, mainly due to the multidimensional and multilevel characteristics of the agricultural sustainability concept (Hayati et al. 2011). One of the key issues is how agricultural sustainability could be defined and measured. The definition of a precise, operational and absolute "Sustainable Agriculture" concept, is a challenging process because it should take into account the variety of "alternative" agricultures such as ecological, regenerative, low-input and organic agriculture (Lockeretz 1988, Dunlap et al. 1993), and also the fact that different stakeholders are susceptible to define sustainability based on their own context and interest (Allen et al. 1991, Dunlap et al. 1993). Since the 1980s, when the sustainable agriculture concept has been widespread, at least 70 definitions can be found in the literature, differing mainly on the type of values, priorities and goals proposed (Hayati 2017). Despite the lack of agreement on a definition of sustainability in agriculture, and considering that sustainable agriculture represents a fundamental requisite for sustainable development at the global level (OECD 2001, Binder et al. 2010), a review of 44 definitions published between 1984 and 2016 stressed that most of the definitions take into account the three pillars or dimensions of sustainability: environmental, social and economic (Hayati 2017). The three-pillars approach is seen as the most comprehensive to define sustainable agriculture, being also reflected in the most suitable definition proposed by FAO (FAO 2014) for identifying and designing sustainable agriculture indicators (Hayati 2017). In that context, some authors suggest that a precise measurement of agricultural sustainability is almost an impossible task because it is a site-specific and dynamic concept (Gennari and Navarro 2019), or it depends on the perspectives of the analysis (Webster 1999). Despite the challenges associated with the lack of a common/agreed measurement of sustainability, the selection of specific parameters or criteria could highlight some positive or negative sustainability trends (Pretty 1995). A variety of indicators and criteria have been developed depending on the socioeconomic-environmental processes, and on the level of the analysis (such as plot, farm, local and landscape level). A review of the variety of indicators used by researchers to measure sustainability on farming systems since the 1980s is provided in Annex 1. The indicators are classified according to the three pillars/dimensions of sustainability, highlighting key economic, social and environmental/ecological assets for sustainability. Many of the socioeconomic indicators highlight the relevance of net farm income, farm production and diversification, access to markets, energy, land, water and biodiversity, food security and sovereignty, opportunities of training and education, gender and age composition, community engagement, local and indigenous knowledge. Moreover, most of the environmental/ecological indicators for sustainability, highlighted in Annex 1 emphasise the importance of soil fertility, the chemical, physical and biological soil quality, biodiversity levels and functions.

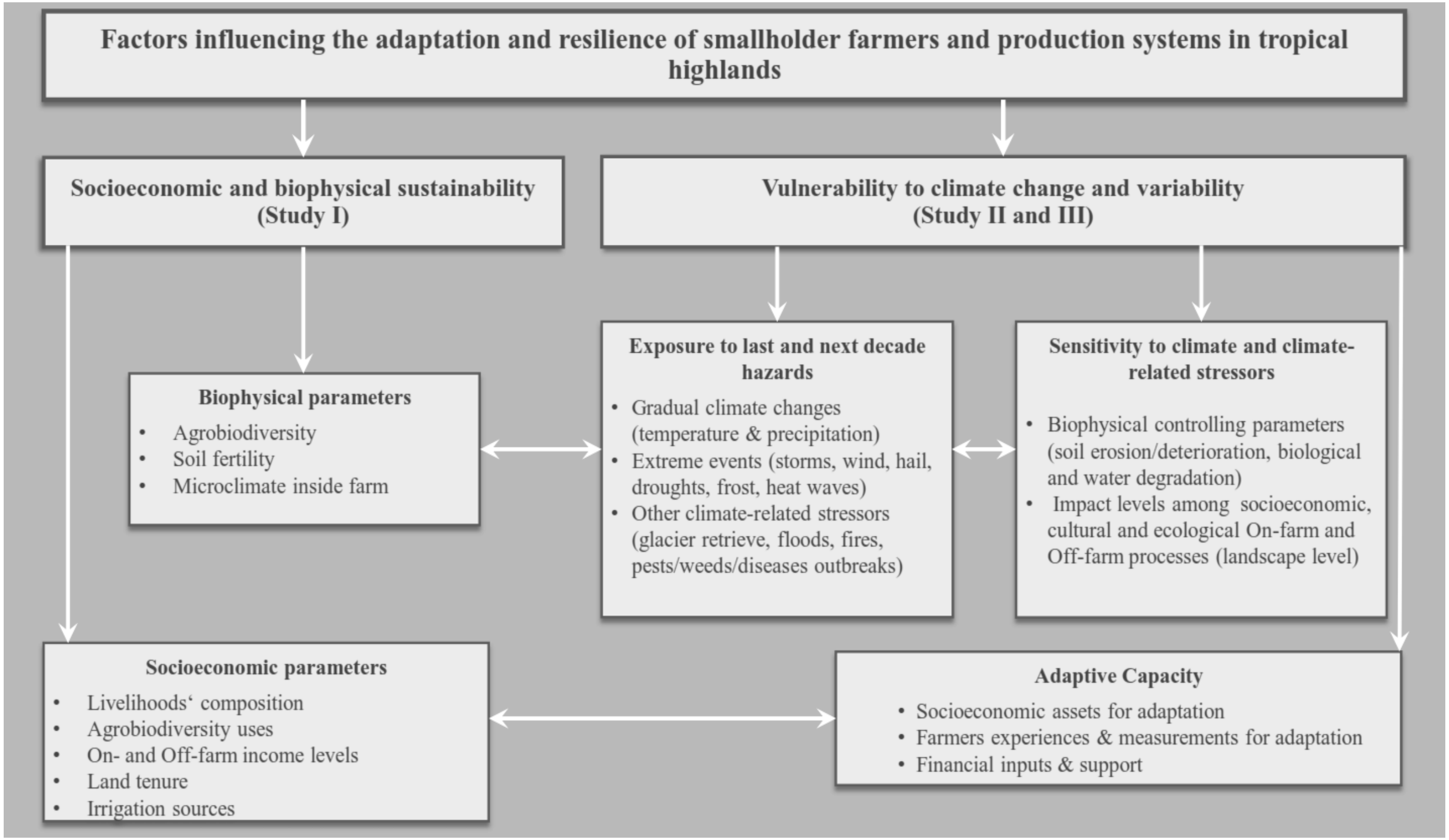

Figure 1. Framework of the study (vulnerability framework based on WOCAT 2017)

Although there is no unique framework that includes all the aspects of sustainability, there are some frameworks developed by a variety of actors, such as civil society, universities and national and international corporations and institutions, which could be considered in the evaluation of farming systems' sustainability, depending on the specific context and the analysis level. A relevant common framework named "driving force state response" (DSR), developed by the Organisation for Economic Cooperation and Development (OECD), identifies 18 indicators describing different socioeconomic and environmental effects and processes related to soil, water, air and climate change, biodiversity, and agricultural inputs and outputs (OECD 2013). However, this approach and most of its indicators evaluate the agricultural sustainability at aggregate level (mostly at national, regional and global scale), presenting limitations when measuring sustainability at farm level (Hayati et al. 2011).

Another interesting approach to measure agricultural sustainability analyses the strengths and limitations related to Sustainable Development Goal (SDG) indicator 2.4.1, "Percentage of agricultural area under productive and sustainable agriculture". Based on 11 sustainability attributes or sub-indicators, this indicator tends to measure the degree of sustainability of each farm, having also the possibility to be aggregated and interpreted at national, regional and global levels (Gennari and Navarro 2019). The 11 sub-indicators included in this approach cover the three dimensions of sustainability, economic (farm output value per hectare, net farm income, and risk mitigation mechanism), environmental (prevalence of soil degradation, variation in water availability, management of fertilisers, management of pesticides, and use of biodiversity-supportive practices), and social (wage rate in agriculture, food insecurity experience scale, and secure tenure rights to land), addressing the minimum objectives that a farming system should reach to be considered as sustainable (UN 2015, FAO 2017, Hayati 2017, Gennari and Navarro 2019). This approach possesses an internationally agreed methodology, having a high potential to be implemented by countries with the technical assistance of FAO (Gennari and Navarro 2019).

Another relevant framework to evaluate sustainability at different levels (also developed by FAO) is the Sustainability Assessment of Food and Agriculture Systems (SAFA) (FAO 2014). SAFA is considered a comprehensive assessment that incorporates all components of aspects of sustainable agriculture, including also the three dimensions of sustainability (economic, social and environmental), and adds an extra governance dimension. The "Good Governance" dimension was added due to the importance of good corporate governance supporting the relations among value chains and different types of stakeholders. To cover the broad spectrum of four sustainability dimensions, SAFA refined 21 core sustainability issues as "Themes" associated with sustainability goals (Annex 2). In turn, each of the 21 sustainability themes, were particularised in 58 "sub-themes" representing specific sustainability goals (Annex 2). Each sub-theme includes a set of default indicators to measure the sustainability performance of the subtheme (Annex 2) (FAO 2013, FAO 2014). Although SAFA could be mostly concentrated on the evaluation of farms or companies as enterprises and their associated supply chains (FAO 2014), this framework takes into account the inputs; outputs and impacts of the production process, adding the extra and comprehensive considerations of good governance and social well-being for sustainable enterprises. Furthermore, SAFA underlines the importance of environmental integrity to successful sustainability. It is reflected in the greater number of indicators designed to evaluate the environmental/ecological sustainability (52 indicators), most of them related to the sustainable management of biodiversity, materials and energy, land/soil and waters sources (Annex 2).

In general, the major requirement for sustainable agriculture stressed by some authors is the sustainable management of land and water resources (Hayati et al. 2011).

2.2. Different approaches for evaluating climate change vulnerability in smallholder farming systems

It is well known that agricultural systems, particularly the smallholder farming sector in the case of developing countries, tends to be highly vulnerable to multiple Climatic and Climate-Related Stressors (CCRS) associated with CCV and socioeconomic changes (Dasgupta et al. 2014, Nazari et al. 2015). This high vulnerability is due mainly by their dependence on natural resources and climate conditions, the prevalence of poverty, lower levels of formal education and employment, isolation, and the lack of supportive climate-related policies (Dasgupta et al. 2014, Nazari et al. 2015, Pandey et al. 2015). Most of the impacts affecting agriculture systems are related to the increase in temperature, changes in precipitation regimes, and intensification in the frequency of ECE, especially droughts (Porter et al. 2014, Settele et al. 2014). Extensive research has shown that the impacts of CCV on smallholder and subsistence systems in developing countries will mostly affect staple crops and livestock, causing a decrease in yields, increasing water requirements, and spreading pests, weeds and diseases (Morton 2007, Dasgupta et al. 2014, Porter et al. 2014). In that context, and considering the socioeconomic and environmental complexity, the context-site specificities and the influence of multiple CCRE, the evaluation of vulnerability of smallholding systems represents a challenging task. Some authors consider vulnerability as a non-measurable theoretical concept or difficult to be directly observed and subjectively measure or quantify, due to its dynamic and context specific characteristics (Nazari et al. 2015, Pandey et al. 2015). On the other hand, many studies identify at least six different schools to evaluate vulnerability in socio-ecological systems: the school of double structure vulnerability; the conceptual frameworks of the disaster risk community; the analytical framework for vulnerability assessment in the global environmental change community; the school of political economy; the holistic approach to risk and vulnerability assessment; and the BBC[10] conceptual framework (Birkmann 2006, Nazari et al. 2015).

Double structure vulnerability considers that vulnerability is the interaction between an external side (exposure to external stressors) and an internal side (the coping capacity of the affected household, group or society). The disaster risk community school, defines vulnerability as a component of disaster risk and differentiates exposure; vulnerability and coping capacity as separate features. Vulnerability in this case is considered mainly as the individual "exposure to hazards" or "being in the wrong place at the wrong time", showing limitations to evaluate the vulnerability of groups or communities whose exposure also depends on socioeconomic drivers. The framework of vulnerability assessment in the global environmental change community (Turner et al. 2003) proposes a broader vulnerability analysis based on the exposure, sensitivity and response capacity, including adaptation responses, as basic components of vulnerability. This framework takes into account the different interactions of stressors in the context of human-environmental systems. The political economy school evaluates vulnerability focused on people, identifying the most vulnerable groups/individuals, the main vulnerability causes and the dynamic pressures. This framework is mostly applied in poverty and development studies (Birkmann 2006, Füssel 2007). In the holistic approach to risk and vulnerability assessment, vulnerability situations

[10] Term linked to the conceptual work done by Bogardi and Birkmann (2004) and Cardona (1999 and 2001).

depend on three factors: the exposure and susceptibility of the physical elements (considered as hard risk and hazard dependent factors); the social and economic fragilities; and the lack of resilience to cope and recover (considered as soft risk and non-hazard dependent factors). Hard risk factors could be directly impacted by hazards, resulting in a potential damage of physical infrastructure and environment, while soft risk factors could present indirect socioeconomic impacts on communities and organisations (Birkmann 2006). The BBC conceptual framework focuses on the social, economic and environmental vulnerability, integrating and linking the sustainable development concept into the vulnerability framework (Cardona 1999, Cardona 2001, Bogardi and Birkmann 2004). This framework emphasises that vulnerability is a dynamic process where exposed/susceptible elements and coping capacities should be analysed at the same time and within the three spheres or pillars of sustainability. Although social and economic vulnerability are considered as core elements in most of the frameworks, the BBC framework stresses the importance of the biophysical elements, represented in the environmental sphere, as an essential component of human life. Therefore, the environment is not only limited to the "hazard sphere", but rather it is closely related with the human society (Birkmann 2006). In addition, the combination of different frameworks in an "Integrated Approach", have been applied to study and integrate the different components and dimensions of vulnerability. An integrated approach usually combines socioeconomic and environmental methodologies to analyse the interactions among the 'internal' factors of a vulnerable system with its exposure to 'external' hazards (Füssel 2007, Nazari et al. 2015). The risk-hazard approach and the political economy approach have been combined into various integrated approaches, being the most relevant the hazard-of-place model (Cutter et al. 2000) and the couple vulnerability framework[11] (Turner et al. 2003). Integrated vulnerability assessments are extensively used in the context of global environmental change at different levels (regions, communities and other social-ecological units), normally being focused on physical stressors such as natural hazards and climate change (Füssel 2007).

Within the framework of "Sustainable Land Management" and "Sustainable Development Cooperation", two interesting vulnerability approaches have been designed based on the needs to understand how the current and projected climatic hazards affect, or could affect, farming systems, communities and livelihoods. The Community-based Risk Screening Tool – Adaptation and Livelihoods (CRiSTAL), is a planning tool developed to mainstream and analyse climate risks, vulnerability and adaptation of livelihoods, especially in developing projects at the local community level (IISD 2012, IISD 2013). CRiSTAL helps users (including project planners and managers) to understand how a project area and local livelihoods are, or will be, affected by current and future climate hazards, putting a special emphasis on the different responses of men and women to current and potential future socioeconomic and environmental impacts of identified climate hazards. CRiSTAL identifies the livelihood resources most affected by current climate hazards, including also the most important livelihood resources for response strategies. In addition, CRiSTAL analyses the project activities affecting the access to, or the availability of, critical livelihood resources. This tool is also useful to revise project activities, or design new ones, in order to enhance climate adaptation and decrease climate risk, establishing the extent of the project contribution to climate adaptation (IISD 2012, IISD 2013). Although CRiSTAL is not considered a comprehensive tool for vulnerability or climate risk assessment, it shows a high potential to be used as a framework to

[11] The human-environmental system and the interactions among social and biophysical capital with experienced exposure and the coping mechanisms.

analyse the vulnerability and adaptation of rural livelihoods to CCV due to its simplicity, practicality, and flexibility to understand the connections between climate risk, vulnerability and adaptation capacities, livelihoods and development projects. Its livelihood and climate-risk (climate variability and change) focus allows users to concentrate on opportunities and capacities rather than only constraints. Moreover, its participatory approach and versatility, relaying on communities' and local experts' knowledge and experience, gives an excellent opportunity to assess local realities, empowering communities and local actors to determine climate adaptation strategies and interventions at different scales (from community to national level) and for different purposes such as the screening of natural resource management projects, agricultural policies, designed adaptation activities or to reinforce parts of a comprehensive climate risk assessment (IISD 2012, IISD 2013).

The framework used in this study as an experimental tool to evaluate (mostly qualitatively) the vulnerability of farming system types or technologies/approaches to CCV, is the Climate Change Adaptation Module (CCA) of the World Overview Conservation Approaches and Technologies (WOCAT). In general, WOCAT is a network designed to document, share and use the data/knowledge in order to support innovation, adaptation and decision-making in issues related to sustainable land and water management (WOCAT 2016d). WOCAT provides a variety of methods and tools to document, monitor, evaluate and disseminate sustainable land and water management practices such as: Questionnaire on Sustainable Land Management (SLM) Technologies, Questionnaire on SLM Approaches, Mapping Questionnaire, Questionnaire on Watershed Management (Module), and the additional module of Climate Change Adaptation Questionnaire (WOCAT 2016b). WOCAT methods and tools are widely accepted and have been recognised by the United Nations Convention to Combat Desertification (UNCCD) as the main recommended database for SLM best practices and adaptation measures (WOCAT 2016c). In the specific case of CCA, this module uses a specialised questionnaire to assess the adaptability of certain SLM technology to climate changes and extremes (FAO 2019). The specificity of CCA means that vulnerability (based on exposure, sensitivity and adaptive capacity of farming systems and farmers) can be evaluated at farm level or individual SLM technologies instead of areas and landscapes, with the facility to visualise the results of the vulnerability analysis using simple graphs and illustrations. Furthermore, the results of the vulnerability analysis using the Climate Change Adaptation Questionnaire can be useful in negotiations with stakeholders to decide which SLM technology should be adapted or entirely changed under different climate change scenarios (WOCAT 2016a).

The IPCC also proposes an interesting approach to analyse how social-ecological systems could be affected by CCV. This framework is focused on the risk of climate-related impacts (resulting from the interactions of climate-related hazards with the exposure and vulnerability of human and natural systems (Oppenheimer et al. 2014). Climate related-hazards that could cause risk are derived from natural climate variability and anthropogenic climate change (mainly produced by increased emissions and land use changes), while the risk of exposure and vulnerability are mainly related to changes in socioeconomic processes such as socioeconomic pathways, adaptation and mitigation actions and governance (Oppenheimer et al. 2014). To refine the analysis, climatic and socioeconomic risks in the IPCC framework are divided into key and emergent risks. Key risks are the potentially adverse consequences derived from high hazard or high vulnerability shown by humans and social-ecological systems, or both, while emergent risks are defined as the resulting risks of the interaction of some phenomena in a complex system, such as the risks arising from human migration due to climate change, which could increase the vulnerability and exposure of the receiving region and populations. The risk-based approach - adopted by IPCC (Oppenheimer et al.

2014, IPCC 2018, Hurlbert et al. 2019, IPCC 2019a) to replace the vulnerability approach (based on exposure, sensitivity and adaptive capacity) (IPCC 2001, IPCC 2007) - is considered a useful process to support decision making due to the focus on the interactions between hazard, exposure and vulnerability. It identifies weather and climate risks, and provides a description of risks including the probability of occurrence, the impacts, and the available response capacity and resources to be more effectively allocated (Connelly et al. 2018, Hurlbert et al. 2019). The different conceptualisation and separation of exposure as part of the vulnerability concept are likely the most relevant aspects that differentiates the risk-based approach from the previous vulnerability-based approach followed by IPCC until its Fifth Assessment Report (AR5). The main difference on exposure concept between the risk-based and vulnerability approaches is that in the earlier approach exposure is mainly related to a place where individuals, communities, natural and social-ecological systems are located and the socioeconomic and environmental circumstances which could be adversely affected by climate and non-climate related hazards. On the other hand, vulnerability-based approach considers exposure as part of vulnerability concept (IPCC 2001, IPCC 2007), being defined as the "nature and degree to which a system is exposed to significant climatic variables" (Füssel and Klein 2006, Connelly et al. 2018), such as long-term changes in average climate conditions (annual mean temperature, precipitation, and sea-level rise) or extreme events (floods, convectional storms, heat and cold waves) caused by natural or anthropogenic climate change. Some authors argue that the risk-based concept adopted by IPCC since AR5, are useful to move the focus from top-down or science-first vulnerability assessments to risk management assessments, where climate change is considered as one risk along with many other challenges. Consequently, it could enhance the involvement of a variety of stockholders, improve the prioritisation of climate change issues, included a better communication of climate change challenges for decision-making (Weaver et al. 2017, Connelly et al. 2018).

The literature review presented above, indicates that the evaluation of vulnerability on social-ecological systems requires to take into consideration at least the main components of the social-ecological systems (social, economic and environmental/ecological), and the interactions with the different CCRE at certain level (regions, sectors, ecosystems, social groups) (Leichenko and O'Brien 2002, Bogardi and Birkmann 2004). For that proposes, and based on the IPCC definitions of vulnerability until AR5 (IPCC 2007)[12] and (Agard et al. 2014, IPCC 2019a)[13], extensive research have evaluated vulnerability commonly analysing the three components: exposure, sensitivity and adaptive capacity (Gbetibouo et al. 2010, Thorlakson and Neufeldt 2012, Lindoso et al. 2014, Nazari et al. 2015, Pandey et al. 2015). In that sense, the evaluation of smallholding farming systems' vulnerability in this study, was based on the WOCAT Climate Change Adaptation Questionnaire Version 2 (WCCQV2) (Annex 4). Although the WCCQV2 takes into account a vulnerability-based approach (so-called 'second-generation') which includes exposure as part of the vulnerability concept, this questionnaire was designed exclusively to evaluate the vulnerability/resilience of farming systems (SLM Technologies in WOCAT terminology), livelihoods and households to CCV. The 138 parameters included in WCCQV2 in this study (Annex 4), represented an articulated and comprehensive data set to compare (mostly qualitatively), the

[12] The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and the variation to which a system is exposed, the sensitivity and adaptive capacity of that system.

[13] The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

vulnerability/resilience of the AFS and CAS. The exposure, sensitivity and adaptive capacity parameters of WCCQV2 show high relevance and level of detail on the biophysical, socioeconomic, cultural and institutional factors and processes in the context of CCV. It is important to remark that the newer version of the WOCAT Climate Change Adaptation Questionnaire (WOCAT 2017) – did not apply in this study- have been harmonised with most of the definitions used by IPCC AR5, including the inclusion of the risk dimension interlinked with potential impacts that influence the sensitivity of the farming system. Therefore, the interactions between exposure + risks and potential CCV impacts affect sensitivity, that combined with adaptive capacity compose the vulnerability/resilience of the farming system (WOCAT 2017). The analysis of biophysical and socioeconomic data included in Climate Change Adaptation Questionnaire is also focused on decision support in order to facilitate the adaptation or change of the farming systems.

3. Materials and methods

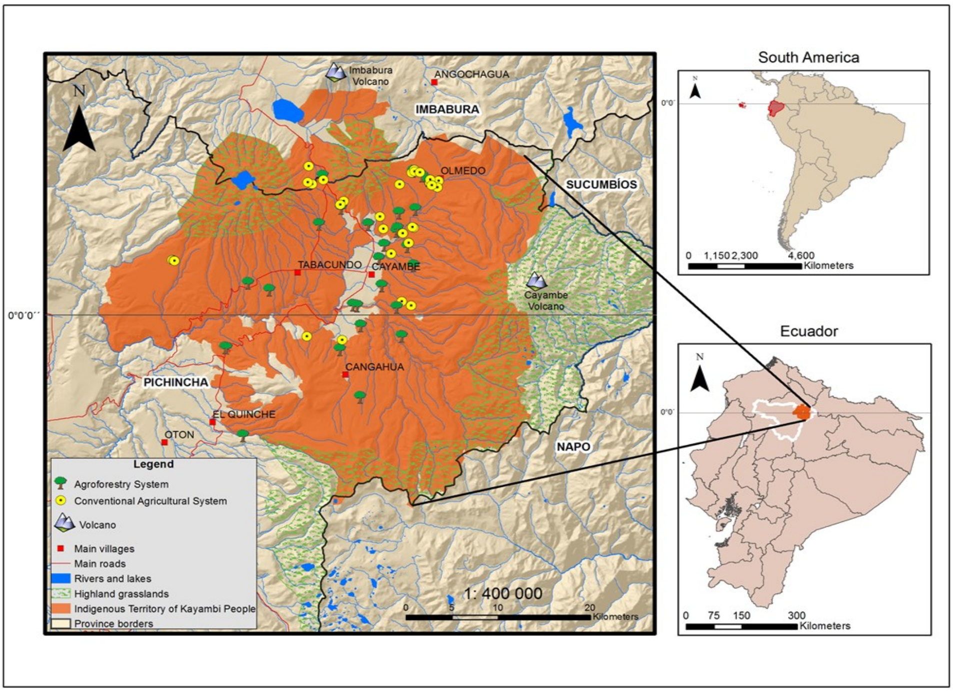

Figure 2. Study area location and sample farms' distribution (Córdova et al. 2018)

The ITKP covers about 1329 Km² (Maldonado 2016) distributed mostly along the rural highlands of three provinces, six cantons, 16 parishes and 168 communities (Pilataxi 2001, Becker 2008, INEC 2010b), at altitudes ranging between 2000 m (Inter-Andean valleys) to 5970 m (Cayambe Volcano). The territory expands along the eastern and western mountain chains, presenting a partially flat topography (Inter-Andean valleys), while the steep slope hillsides have been affected by erosive processes (Knapp 1991). These geomorphological and topographic features, influenced also by the equatorial zone location, have formed a wide range of bioclimatic zones (Cañadas 1983, Medina and Mena 2001).

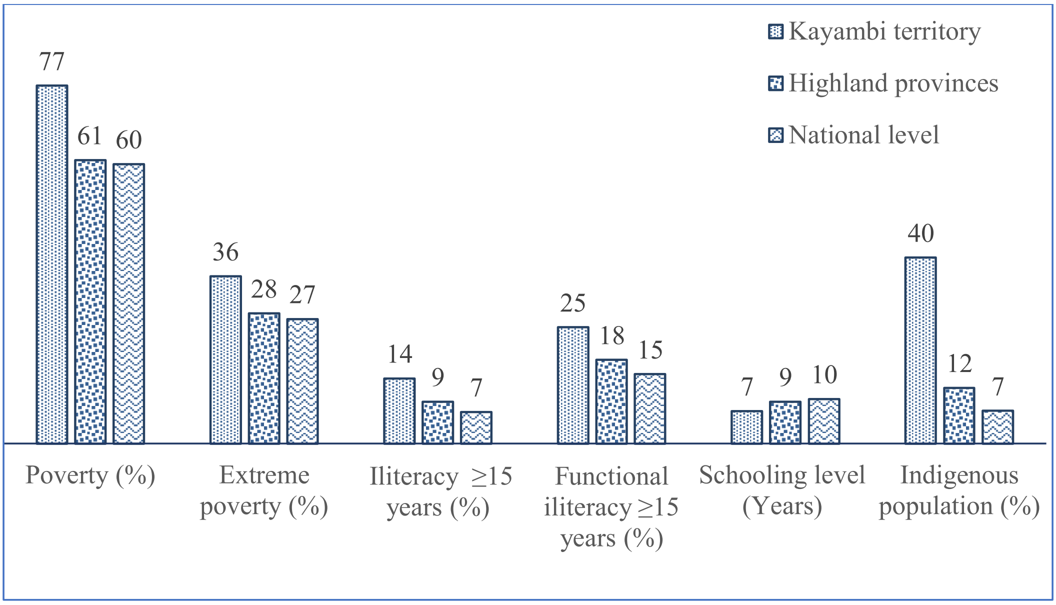

Figure 3. Main socioeconomic indicators' differences among Kayambi territory, highland provinces and national-level (Córdova et al. 2018).

Figure 4. Study area landscapes

Figure 5. Kayambi people

The ITKP includes areas under agricultural production and native ecosystems, principally moorlands or *Páramo*. The soils are characterised by their fertility formed from volcanic ash; classified as inceptissols, mollisols and andisols (Moreno 2015). Rainfall and temperature in the ITKP vary depending on topography, altitude, the proximity to the equator, and the influence of frequent air currents formed in low inter-Andean valleys (Cañadas 1983, Medina and Mena 2001). Rains are more frequent from September to April, presenting a mean annual rainfall range of 250 to 2000 mm (INAMHI 1970, Cañadas 1983). Temperature also varies depending on the location, with low inter-Andean valleys usually dry with annual temperatures between 12 to 18 ˚C, while moorland areas are humid and colder with annual temperatures between 3 to 6 ˚C (López 2013). The ITKP has a population of approximately 154447 inhabitants, 40% of them self-recognizing as indigenous people (INEC 2010a) (Figures 4 and 5). The indigenous population is distributed along the whole territory, representing more than 90% of the inhabitants in some highland areas (Córdova et al. 2018). This indigenous cultural dominance along the territory influences the landscape in terms of land management practices.

The ITKP is considered by Kayambi people as an ancestral territory, managed according traditional customs and under formal consolidation and recognition (Pilataxi 2001).

The sampled farms included in this study were distributed along highlands, between 2500 to 3300 m.a.s.l (Figure 4 and 5). In Ecuador, lands located at these altitudes are very suitable for food production, especially in the case of vegetables and tubers, which are consumed locally and in the rest of the country, therefore playing an important role in the country's food security (Knapp 1991, Suquilanda 2011, Oyarzun et al. 2013). On the other hand, in farmlands with irrigation facilities, crop production has been replaced by dairy farming due to its competitive advantages (less complex systems, less workload inputs and more private and public promotion and support) compared to other local farming systems (López 2013, Moreno 2015, Velasco et al. 2018). Agricultural production in the study area is usually based on traditional permanent and temporary monoculture crops (legumes, maize, potatoes, vegetables and pastures). Although the use of synthetic fertilisers and pesticides are used extensively, some traditional agricultural practices still persist, such as crop rotation/association and organic fertilisation. Alternative management practices such as agroecology, agrosilvopasture, and agroforestry systems, are also implemented in some places. Most of the production is focused on subsistence/self-consumption and local commercialisation.

In many cases the sampled farms in this study were located in the transition zones between farmland and native ecosystem remnants, mostly moorlands and Andean forests around the Cayambe and Imbabura volcanoes, and the villages of Cangahua, Olmedo and Tabacundo (Figures 2 and 4). The native ecosystem remnants, especially moorlands, constitute a highly sensitive and key mountain ecosystem responsible for the regulation and supply of fresh water to local and distant cities' populations (Urrutia and Vuille 2009, Schoolmeester et al. 2016). The expansion of agriculture and dairy farming activities have been the main drivers of moorlands depletion, putting the water regulation and supply functions of these ecosystems at high risk, in the global change context (Hofstede 2001, Schoolmeester et al. 2016).

The study area was selected based on: the availability of at least 60 smallholder farms, especially with agroforestry practices, in highlands (between 2500 to 4000 m.a.s.l); farmers' livelihoods principally based on agricultural activities; and farmers' interest and good predisposition to collaborate with the study. Other important criteria used to choose the ITKP as the study area were the special interest in the research and the facilities provided by the Kayambi People's organisation (for example the involvement of the community leaders promoting and validating the research; and the provision of local technicians for logistic and cultural support). Another consideration was the better logistic aspects to reach and work in the area, such as secure social environment, safe road infrastructure, easy and quick access. It is important to remark that the selection of the study area was a result of a pre-assessment conducted by the researcher in four highland provinces (as indicated in Section 1.4). In that sense, the researcher first made formal contact with the indigenous organisations in each province to apply for permission to conduct the rapid evaluations. The self-recognition of the researcher as a Pasto indigenous person, and the experience gained working with indigenous organisations and leaders in these four provinces was undoubtedly an important advantage to get the social and political acceptance to do the pre-assessment in these territories and also in the ITKP. The researcher was always accompanied and supported by a local leader or technician appointed by the indigenous organisation in each province. The pre-assessment was very useful to evaluate some conditions related to the planned field work (accessibility and road conditions, availability and distribution of smallholder farming systems, perceptions of the social environment and safety conditions, and to gage the interest of farmers and indigenous organisation to participate in the research).

3.2. Sampling and data collection

The study includes 60 sample farms randomly selected from a total of 633 smallholder farms belonging to the local smallholder farmer organisation RESSAK (Network for Food Sovereignty and Solidarity Economy of the Kayambi territory) (Otavalo Unpublished results). These farms are part of the approximately 12000 smallholder farms in the whole ITKP (CODEMIA Unpublished results). The 60 sample farms were selected by the researcher and local Kayambi technicians, taking into account three main considerations: (1) farm size, up to 10 ha (FAO 2012); (2) altitude between 2500 and 4000 m.a.s.l; and (3) the quantity of trees and/or shrubs. An easy and quick criteria to classify farms as agroforestry or conventional systems was the percentage of farmland covered by trees and/or shrubs (Zomer et al. 2014b). If at least 10% of the farmland area was covered by trees and/or shrubs in any spatial design, the farm was classified as being an agroforestry system (AFS) (Figure 6). On the other hand, if less than 10% of the farmland area was covered by trees and/or shrubs, the farm was considered as being a conventional system (CAS) (Figure 7). The sample farms were distributed along the ITKP in different bioclimatic zones mainly located in the upper inter-Andean valleys, foothills and gorges (Figures 2, 3, 6 and 7). AFS sites were difficult to find because these systems are scattered throughout the territory, being less commonly practiced than conventional systems (which are characterised mainly by annual or seasonal croplands and permanent pastures). Consequently, the use of villages/communities as a unit for comparison was not possible, because individual villages/communities had very few agroforestry farms. This pattern is extended along the whole Ecuadorian highlands where conventional systems have been more implemented as a result of colonisation and the consequent production approach changing (Hofstede et al. 1998).

The selection of an individual farm/household as a comparison unit instead of community was determined when choosing the suitable method to collect the data, influencing also the logistics arrangements, the time invested, and the quality of the data. If agroforestry was an extended practice in the study area, with the possibility to consider villages or communities as a comparison unit, the method used to collect data could have been different, focussing instead on focus group discussions, complemented with key informants' interviews. In that was the case, then the use of long, semi-structured household questionnaires would not have been possible, and the quantity and the specificity of the data would have been very limited with different kind of results.

Figure 6. Agroforestry systems in the ITKP

Figure 7. Conventional agricultural systems in the ITKP

To collect the data, 60 interviews were conducted at household level with women farmers (73%), farmer couples (17%), and male farmers (10%). The interviews in Study I were carried out through semi-structured questionnaires which contained basic biophysical and socioeconomic data related to the farming systems' sustainability (Annex 3). In the case of Studies II and III, interviews were conducted using a modified WCCQV2 (Annex 4). As was previously mentioned in Section 2.3, WCCQV2 was used in this study due to its high level of detail for the analysis of vulnerability, including the exposure and sensitivity of highland farming systems to climatic and climate-related stressors (CCRS), and the adaptive capacity of smallholder farmers' livelihoods and households. Sections 2.2 (Timeline: frequency of ECE to which the technology has been exposed in the last 10 years), 2.3 (Seasonal calendar of climate change observations), and 2.4 (Crop seasonal sensitivity) of the questionnaire, were simplified to optimise and facilitate the interviews. As a substitute for these very detailed sections in the questionnaire, farmers were instead asked to describe and prioritise the main gradual climate changes, extreme climatic events and other CCRS that have affected their farming systems during the last 10 years (Annex 4).

The 60 interviews were conducted directly by the researcher from December 2015 to May 2016. The complete interview consisted of two parts. The first part included all the information related to the biophysical and socioeconomic parameters for the analysis of sustainability (Figure 1 and Annex 3), while the second part covered the exposure, sensitivity and adaptive capacity information considered in the vulnerability analysis (Figure 1 and Annex 4). The first part of the interview took an average of two hours to conduct and was preceded by a direct observation of the farmland. This process was led by the farmer who freely showed and explained the main characteristics and interactions of the biophysical and socioeconomic components of the farming system. This approach to beginning the interviews was an excellent strategy to engage the farmer and enhanced the interaction with the researcher. The second part of the interview was usually conducted on a different day and also took approximately two hours to complete due to the need to provide adequate explanations of the underlying concepts for some of the more complex parts of the questionnaire (such as the biophysical capacity of the systems to control the impacts of extreme climatic events and gradual climate changes, or the on and off-site economic, cultural, and ecological impacts).

At each sample farm, a set of photographs was taken usually at the end of the first part of the interview, in order to document the farmland distribution, the crops and farm animals present at the time of the interview, and also the farmer and other household members. Most of the data collected represents the perceptions of smallholder farmers about different elements influencing the sustainability and vulnerability of their farming systems and livelihoods. To guaranty the quality of the data, all the interviews were conducted by the researcher and entered directly into a laptop. In addition to household interviews, a subsample of 16 farms (eight AFS and eight CAS) were randomly selected from the 60 sample farms to collect data about soil fertility and microclimate conditions inside the farms. The main reasons to only select 16 subsample farms were the limitations of budget and time. Soil samples were collected and evaluated in a laboratory, while microclimatic data were collected through a Davis Vantage Pro2 micro weather station, placed at the centre of the farm. The micro weather station logged data automatically every 30 minutes for one week in each farm.

The sustainability of the farming systems was analysed taking into account the biophysical and socioeconomic components. Agrobiodiversity, soil fertility, and microclimate conditions inside the farm were the main parameters considered for the analysis of the biophysical component, while livelihoods' composition, agrobiodiversity uses, on-/off-farm income levels, land tenure, and irrigation sources were included as parameters for the socioeconomic component (Figure 1). Agrobiodiversity data were collected considering two categories, cultivated and associated biodiversity (Annexes 3 and 5). The cultivated biodiversity are all the species, cultivars and breeds introduced and managed by farmers. This part of agrobiodiversity plays an important role maintaining food security and enhancing cash income generation. Cultivated biodiversity was divided into 11 subcategories: Trees and shrubs; Legumes and grains; Tubers and roots; Non-tree and shrubs fruits; Vegetables, Pastures, Medicinal, aromatic and condiments; Livestock (ruminants and pseudo-ruminants: cattle, sheep, goats, llamas and alpaca); Minor animals (guinea pigs, rabbits, pigs, chickens, turkeys, ducks, quails and geese); and Other (draught animals, ornamental and cultural spp.). Associated biodiversity includes all the wild plant and animal species founded in the farm, which play a key role supporting the ecological functions of the system, having also the potential to enhance the food security of farmers' households (subsistence functions), and generate income. Agrobiodiversity data were collected and registered as a progressive checklist. For that purpose, farmers were asked about all the species and their uses according to each category and subcategory (Annex 3). Each species, cultivars, and breeds were registered in the respective matrix in the checklist (Annex 3). Thus, the checklist was utilised for the next interviews and when the farmer indicated the use or presence of new species, cultivar or breed, new registers were added to the progressive checklist. At the end of the 60 interviews, very few new registers were added to the list.

In the case of socioeconomic parameters, most of them were collected through semi-structured questionnaires. For the livelihood composition, farmers were asked to describe the livelihood activities and prioritise them based on their highest cash income activity. It was important to categorise the main livelihoods activities and identify which on- or off-farm activity the livelihood portfolio was economically based. On-farm income activities were related to the production and commercialisation of farm products, included dairy farming, while off-farm income activities were related to wages mostly obtained from the construction and fresh-cut flower industries. On- and off-farm incomes were categorised according three levels (high, moderate and low) and taking into consideration the Minimum Ecuadorian Wage (MEW), which in 2016-2017 was fixed to 375 USD. When the monthly household income was greater than one MEW, it was considered as a high level income, while the income was one MEW it was classified as medium level income, and if the income was less than one MEW, the income was considered as low level income. To determine how the agrobiodiversity species were used, two main uses were considered: subsistence-functional and commercial use. The subsistence or functional species were the species used to fulfil farmer's basic needs (usually food, medicine or fodder), or to support farming systems' functionality (normally as pollinators and predator-pest control species). A species was classified as commercial when the species or a product derived from it were used mainly for the provision of cash income. To classify if the species belongs to the subsistence or commercial category, the farmer indicated the amount of the production (in %) allocated to subsistence (family consumption) and the amount for commercialisation. If more than 50% of the production was allocated to family consumption the species was registered as subsistence species with a value of 1 and vice versa. In the case when the production was used in the same proportion for subsistence and commercial purposes (50% and 50%), the species was considered as a mixed used species and registered with a value of 0.5 for subsistence and 0.5 for commercial purposes (Annex 3). To collect land tenure data, three categories were included: formal, informal and mixed tenure. Formal tenure was considered when the property right of the land was fully recognised and state protected, while informal tenure meant that the land was not officially recognised but the access and control are recognised by community and customary laws. The mixed land tenure category included the farmers holding some part of their lands as formal and other part as informal tenure. Finally, to categorise the main irrigation sources as the last parameter to evaluate the socioeconomic farming systems' sustainability, farmers were asked about their dependency on rainfall, the type of irrigation systems they had, and their practices of water storage and harvesting.

The data related with farming systems and farmer's livelihoods vulnerability (exposure, sensitivity and adaptive capacity) were collected using a modified WCCQV2, as was previously mentioned. To collect exposure data, farmers were asked about their perceptions on the gradual climate changes (temperature and precipitation during different seasons), extreme events (heavy rainfalls, hail and wind, droughts/dry periods, heat waves/warm periods and cold periods/frost) and other CCRS (glacier retreat, thunderstorms, pest, disease and weed outbreaks, floods, etc.) for the past and coming decades (Annex 4). Farming systems' sensitivity data included the perceptions of farming systems' biophysical capacity to control the impacts of the main gradual climate changes, extremes and other CCRS, identified and prioritised by farmers in the beginning of the sensitivity section (Section 2 in Annex 4). To complement the biophysical sensitivity of farming systems, the questionnaire included a comprehensive section related to the impact levels of the main CCRS in different socioeconomic, sociocultural, and ecological components, and the processes and attributes of the farming systems and livelihoods at the farm and landscape levels (Section 3 in Annex 4). To complete the vulnerability data, farmers were also asked about their adaptive capacity opportunities to deal and cope with CCV. The adaptive capacity section included information related to the socioeconomic assets of farmers´ households; the knowledge and experiences of farmers for adaptation; and the specific economic inputs invested in adaptation measures, including the kind of support available for adaptation (Sections 4-7 in Annex 4).

3.3. Data analysis methods

Most of the data in this study represent qualitative data based on farmers' perceptions, except the data from agrobiodiversity, soil fertility, microclimate conditions, and the annual economic inputs invested by farmers to support adaptation. The different characteristics of the farming system types were analysed applying a comparative analysis approach. Qualitative variables were analysed through descriptive statistics (Crosstabs and Chi-square), while inferential statistical test (Independent Samples t Test) was applied for the quantitative variables. In the specific case of farmer's perceptions on farming system's exposure to changes in temperature and precipitation, Mann–Kendall tests and Sen's slope estimations were conducted to determine if the trends perceived by farmers in the study area correspond to climate changes or to climatic variability (inter/intra-annual variability - between the years or between the seasons, respectively-). The perception data was compared to official climatic data collected by the National Institute of Meteorology and Hydrology (INAMHI) in the study area during the last decades. The analysis was carried out using MAKENSES tool developed by the Finnish Meteorological Institute (FMI 2002, Salmi et al. 2002).

4. Results

4.1. Biophysical factors influencing the sustainability of agroforestry and conventional agriculture systems (Study I)

4.1.1. Agrobiodiversity (Study I)

The agrobiodiversity perceptions shown in Figure 8 and Annex 5, indicated significant differences between agroforestry and conventional agriculture systems. Total agrobiodiversity is 20% higher in AFS than CAS ($p \leq 0.001$), while the cultivated[14] and associated biodiversity[15] are 30% and 8% higher in AFS respectively ($p < 0.001$ and $p \leq 0.05$).

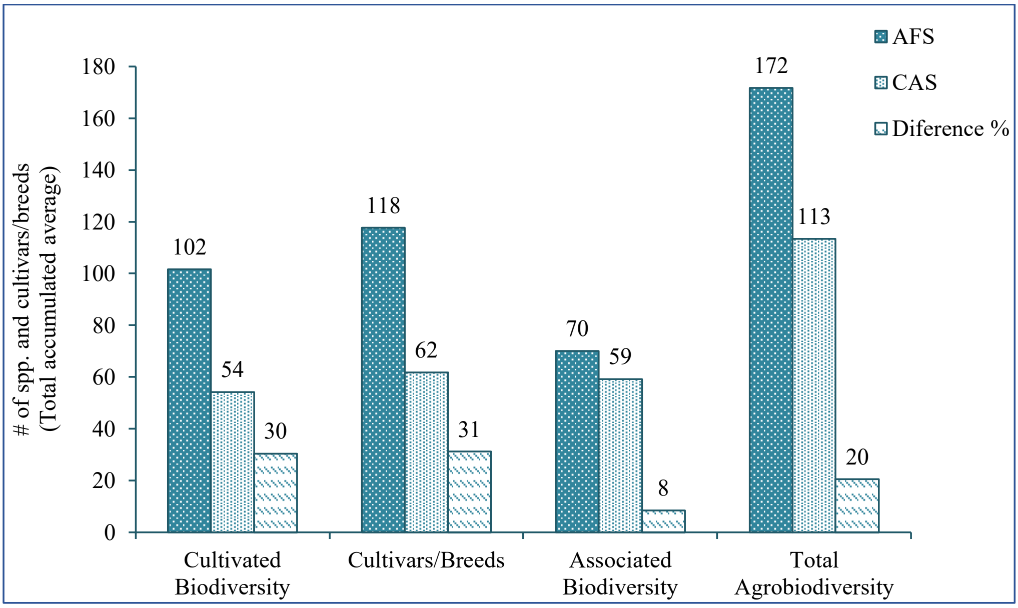

Figure 8. Summary of agrobiodiversity differences between AFS and CAS (based on Table 1 in Study I (Córdova et al. 2018)).

Most of the subcategories included in cultivated biodiversity, except livestock species, show statistically significant differences between systems, with AFS having a higher number of species

[14] All the species, cultivars and breeds managed and controlled by the farmers within the system.
[15] All the wild plant and animal species found within the system, having a variety of socioeconomic and environmental functions (food, medicine, fodder, pollinators, predators-pest controllers, etc.).

than CAS. Moreover, the number of cultivars and breeds[16] are higher and statistically significant in most of the cultivated diversity subcategories, with the exception of livestock breeds.

In the case of associated biodiversity, AFS contained statistically significant higher levels of wild plants and animals than CAS, with birds, amphibians and mammals more frequent in AFS, while the frequency of reptiles and invertebrates are similar in both system types.

4.1.2. Soil fertility (Study I)

The results of soil fertility parameters indicated similar conditions between AFS and CAS (no statistically significant difference between systems), except for the lower levels of phosphorous in the case of CAS ($p \leq 0.05$) (Annex 6). Lower levels of phosphorous could reduce the potential yields, affecting the metabolism of plants, root system development, vegetative growth and the fruit and seed quality (Espinoza et al. 2006, Spargo et al. 2013). Most of the soil in both systems were classified as sandy loams, a type of soil seen as suitable for the majority of crops, including tress and pastures, preferably under frequent irrigation and low surface pressure in order to prevent compaction (Hull 1992, USDA 2001, Kavdir et al. 2014). The low bulk density levels in both systems indicate no soil compaction problems, while the field capacity values denote optimal conditions to retain water for the normal development of crops, trees and pastures. Normally, the total available water content in sandy loan soils[17] could reach 20% (20 g of water/100 g of soil) and present some limitations in the access to available soil water, especially for shallow rooted crops, such in the case of most vegetables and pastures species (Cornell University 2010, Dodd et al. 2011, USDA 2013). In addition, the soil fertility evaluation conducted by the soil and water laboratory of the Salesian Polytechnic University[18] (Annex 6), indicated optimal conditions for most of the analysed soil fertility parameters in both systems. It is noteworthy to consider that the non-significant differences among soil fertility parameters between AFS and CAS may have been due to the small subsample size used in this study[19].

4.1.3. Microclimate conditions inside farms (Study I)

The lack of statistically significant differences between AFS and CAS ($p > 0.05$) in microclimate measurements inside farms may also be due to the small subsample size (Annex 7). However, any small variation in microclimate conditions[20], especially in mountain farming systems were the environmental conditions could quickly vary during the course of a day, may represent important factors limiting or promoting the development of many crops and animals species/varieties and breeds (Price 1995, Zimmerer 1999, Beniston 2003). In that sense, the results of Figure 9 and Annex 7 denote slightly warmer conditions and lower wind speeds in AFS microclimates. The slightly more favourable microclimate conditions shown by AFS is most likely due to the influence of trees and/or shrubs in these type of systems. However, due to the small subsample size and the short data collection time period utilised[21], it was not possible to establish any statistically significant differences between systems and conclude that more favourable microclimate conditions were found in AFS.

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[16] Cultivated genetic diversity, which could have an enormous potential to enhance smallholder farmer´s adaptation in a global change context.
[17] The portion of water available for plants as a result of the difference between field capacity and wilting point.
[18] The common interpretation and recommendations given to farmers to keep the soil fertility at optimal levels.
[19] Mainly due to time and economic limitations.
[20] Such as temperature, humidity and wind velocity.
[21] 16 farms (8 AFS and 8 CAS) and seven consecutive days of microclimate registers for every farm

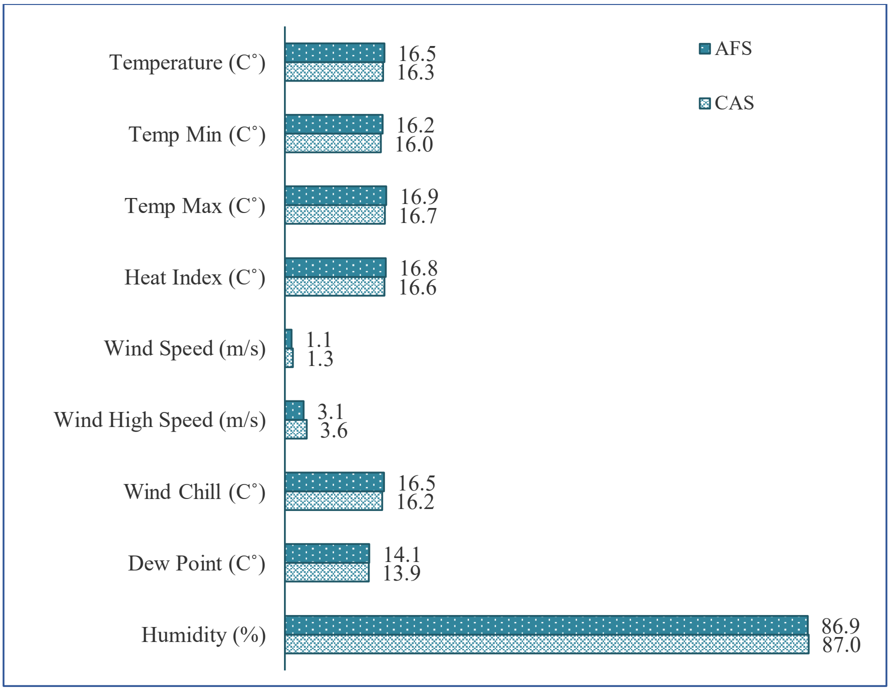


Figure 9. Main microclimate conditions in AFS and CAS (Based on Annex 7).

4.2. Socioeconomic factors influencing the sustainability of agroforestry and conventional agriculture systems (Study I)

4.2.1. Livelihoods (Study I)

The livelihood portfolios shown in Figure 10 were categorised and prioritised by farmers taking into consideration the main activities that support the subsistence and economic needs of their households. To prioritise the livelihood activities, farmers were asked to describe all the activities that contribute to their livelihoods, starting from the most important cash income activity to the least important (Section 3 in Annex 3,). As a result, seven livelihood portfolio categories were identified (Figure 10). Each category includes several activities that support the subsistence and economic income of smallholder households. Figure 10 indicates that livelihood portfolios of agroforesters are more diversified and complex than livelihoods of conventional farmers. Agroforester's livelihoods include all seven categories identified, while the livelihoods of conventional farmers only include five categories. Most of the agroforesters' cash income activities depend mainly on the commercialisation of their own farm products (40%), while in the case of conventional farmers only 17% of their livelihoods depend on the same main cash income activity. In contrast, the majority of conventional farmers' cash income activities rely mainly on dairy farming (37%), while only a small amount agroforesters' livelihoods (3%) depend exclusively on this cash income activity.

It is important to remark that dairy farming in combination with other cash income activities, such as farm products commercialisation and subsistence farming, are more important for the livelihoods of agroforesters (20%) than in the case of conventional farmers (7%). Additionally, a proportion of conventional farmers' livelihoods depend exclusively on off-farm work activities[22] (33%), while in contrast only 17% of agroforesters' livelihoods are based exclusively on off-farm work. The more diverse agroforester's livelihood portfolios is demonstrated by the higher percentage of households combining on-farm activities with off-farm work (20%), in contrast with only 7% of conventional farmers' who combine on-farm livelihood activities with off-farm work.

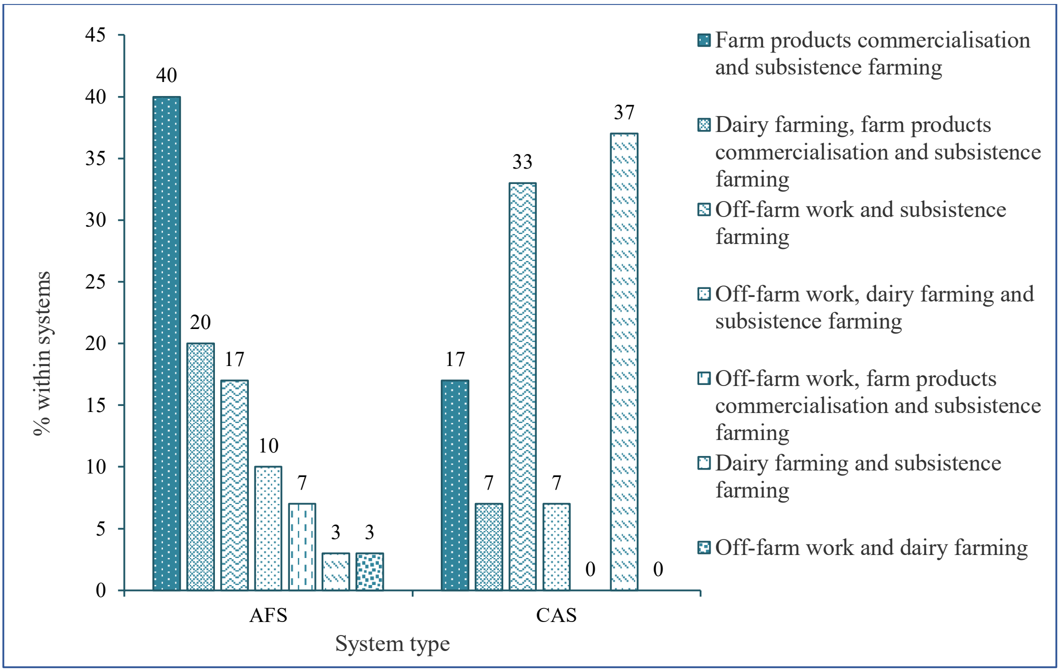
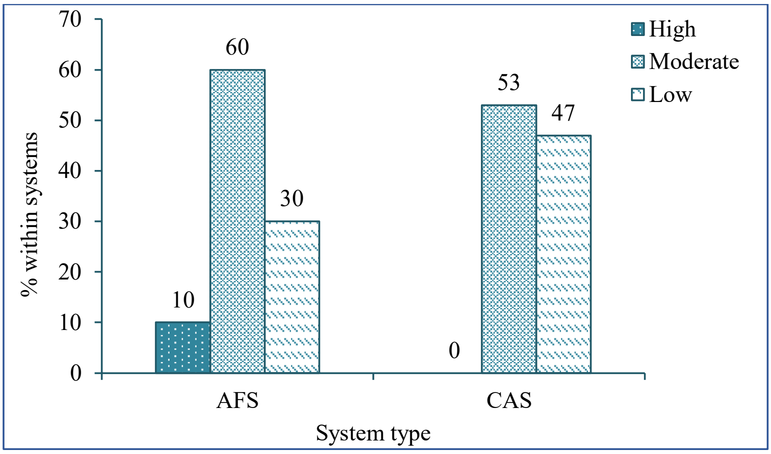


Figure 10. Characterisation and prioritisation of livelihoods portfolios based on cash income activities in AFS and CAS (modified based on Figure 4 in Study I (Córdova et al. 2018)).

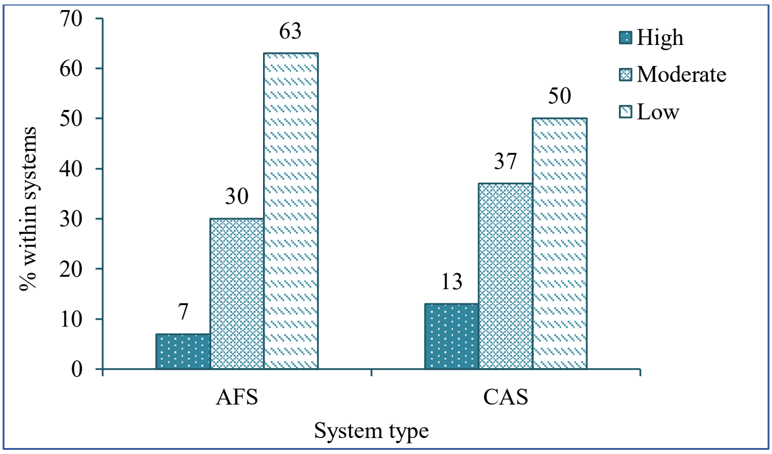
4.2.2. Income levels (Studies I and II)

Figure 11 presents a summary of the farmers' perceptions on the quality and importance of on and off-farm income at the household level. The results emphasise the greater importance of on-farm income to support the livelihoods of agroforesters (Figure 11a). The majority of agroforesters (70%) considered that their on-farm income levels were high and moderate (10% and 60% respectively), while most of the conventional farmers considered their on-farm income level as moderate (53%), with an important fraction indicating a low quality on-farm income (47%). Weak statistical evidence of the greater importance of on-farm incomes for agroforesters was also found between AFS and CAS in Table 6 ($p \leq 0.1$). Although no statistically significant difference was found in off-farm income between systems (Table 6), the results shown in Figure 11b indicate that off-farm income is less important for agroforesters, with most of agroforesters (63%) considering that their off-farm income to be of low importance and only 37% qualified this income as high and moderate importance (7% and 30% respectively). In contrast, half of the conventional farmers qualified their off-farm income as being of high and moderate importance (13 % and 37% respectively), while the other half considered this type of income as low importance.

[22] Usually men are employed as labourers in flower plantations or as construction workers in nearby cities.



(a)



(b)

Figure 11. Farmers' perceptions on the quality and importance of on-farm (a) and off-farm (b) income levels, categorised by system type (modified based on Figure 5 in Study I (Córdova et al. 2018) and Table 1 in Study III).

4.2.3. Main agrobiodiversity uses (Study I)

The use of agrobiodiversity was included in the study due to its importance supporting agroecosystems' functionality; food sovereignty and security; household economies and livelihoods of smallholder farmers (see Annex 8 for detailed results). To evaluate the contribution of agrobiodiversity to maintaining or enhancing the livelihoods of smallholders, two species categories were established: commercial and subsistence-functional species. A commercial species refers to a species or its derived products that is mainly used to generate economic incomes, while subsistence or functional species - including the associated products - are used to provide basic household needs (usually food, medicine or fodder), and are an intrinsic element to support the functionality of the agroecosystem (for example the pollinator and predator/pest control species).

The results in Figure 12 and Annex 8 show a statistically significant difference ($p \leq 0.001$) between AFS and CAS in the number of species for every main use category. Agroforesters used 17% more subsistence/functional species (46 spp.), and 56% more commercial species (12 spp.) than conventional farmers.

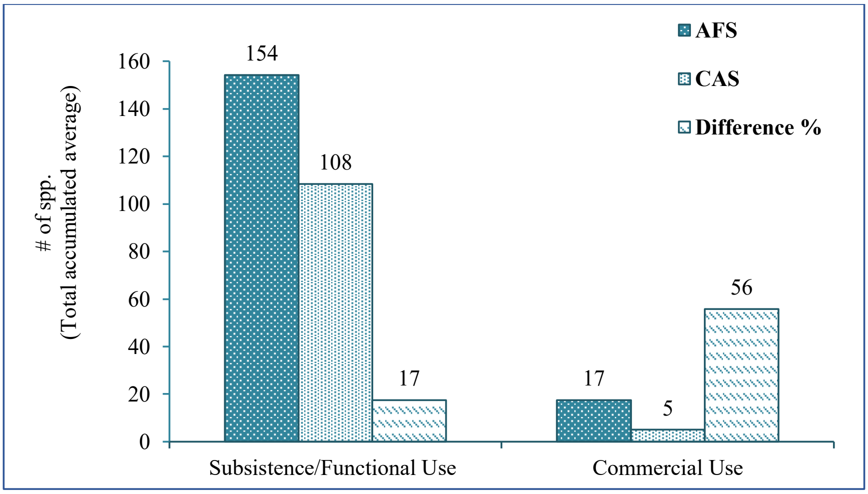


Figure 12. Main agrobiodiversity uses differences between AFS and CAS (based on Annex 8).

Agrobiodiversity categories (cultivated and associated biodiversity) also have statistically significant differences between agroecosystems. Agroforesters used 26% more cultivated species (35 spp.) for subsistence farming and agroecosystem functionality than conventional farmers ($p \leq 0.001$). Additionally, agroforesters used 56% more cultivated species (13 spp.) for commercialisation than conventional farmers ($p \leq 0.001$). Within the cultivated agrobiodiversity sub-categories, the greatest statistical difference in the main usage of subsistence and functional species was found in trees and shrubs ($p < 0.001$). Agroforestry farmers use 43% more cultivated species of trees and shrubs (19 spp.), 39% more other species (four species, $p \leq 0.05$), and 34% more medicinal, aromatic and condiments (four spp., $p \leq 0.001$) for subsistence farming and agroecosystem functionality than conventional farmers (Annex 5). Among cultivated species used for commercial purposes, vegetables had the most statistically significant difference between agroecosystems (six spp., $p < 0.001$), followed by medicinal, aromatic and condiments (two spp., $p \leq 0.05$) and legumes and grains (one spp., $p \leq 0.05$). Regarding the use of associated biodiversity, agroforesters used 9% more subsistence and functional species (11 spp.) than conventional farmers ($p \leq 0.05$). Additionally, there was no statistically significant difference between systems in the commercialisation of wild animals and plants (Annex 8), therefore it did not represent an important economic income generation activity for either agroforesters or conventional farmers.

Agrobiodiversity use results highlight the importance of agrobiodiversity in supporting smallholders' livelihoods (for example contributing to household economies and fulfilling basic subsistence needs such as food, medicine and fodder), and on the other hand contributing to maintain the ecological functions of agroecosystems. These benefits are more relevant for agroforesters than conventional farmers.

4.2.4. Land tenure (Study I)

Land tenure between systems was analysed through three categories: formal, informal and mixed land ownership. Formal land tenure implies that property rights are officially recognised and protected by the state, whereas informal land tenure is when property rights are not fully recognised and protected by the state (but the access and control of the land could be recognised by the community and customary laws). In the case of mixed land tenure, some part of a household's land holdings could be formally recognised by the state, while another part is only recognised by the community and customary laws.

Land tenure results shown in Figure 13 indicate that although all the farmers in this study have access to farmland as private users (an average of three hectares), agroforesters had more secure property rights than conventional farmers. Most of agroforesters (60%) are formal owners of the land, while only 27% of conventional farmers have the similar tenure. On the contrary, a greater proportion of conventional farmers (43%) had mixed land tenure, while only 33% of agroforesters had mixed land tenure. In addition, informal/insecure land ownership is higher for conventional farmers (30%) than agroforesters (7%).

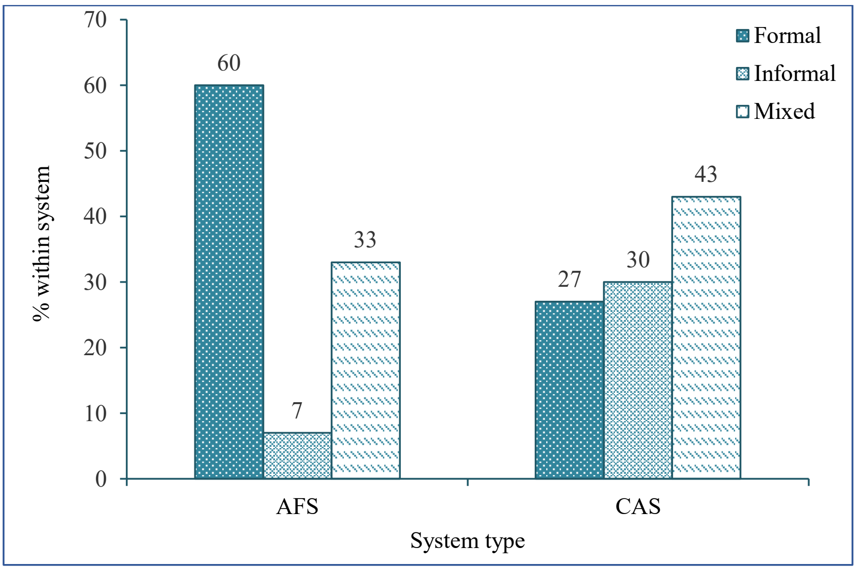


Figure 13. Land tenure categorisation by system type (modified based on Figure 6 in Study I (Córdova et al. 2018)).

4.2.5 Irrigation sources (Study I)

The results presented in Figure 14 describe the main irrigation sources and systems used by smallholder farmers in this study. Agroforesters had more diversified irrigation sources and systems (six categories) than conventional farmers (four categories). Conventional farmers are more dependent on rainfed methods for cultivation (56%) than agroforesters (29%). In contrast, 70% of agroforesters access surface water through communal systems that use some kind of irrigation method, while only 43% of conventional farmers have similar water access, distribution and irrigation methods. It is important to remark that in the context of climate change and adaptation measures, mountain farmers with access to a communal irrigation water distribution system, who apply some water-use efficient method and have the possibility to harvest and keep water in own reservoirs, could be the best prepared to deal with water stress and changes on precipitation regimes. In that context a greater group of agroforesters (17%) than conventional farmers (3%) in this study, fulfil the requirements described above.

The results presented in Figure 14 indicate that the more diverse irrigation sources and lower dependency on rainfed agriculture puts the agroforesters in a better position to maintain and enhance their livelihoods than the conventional farmers.

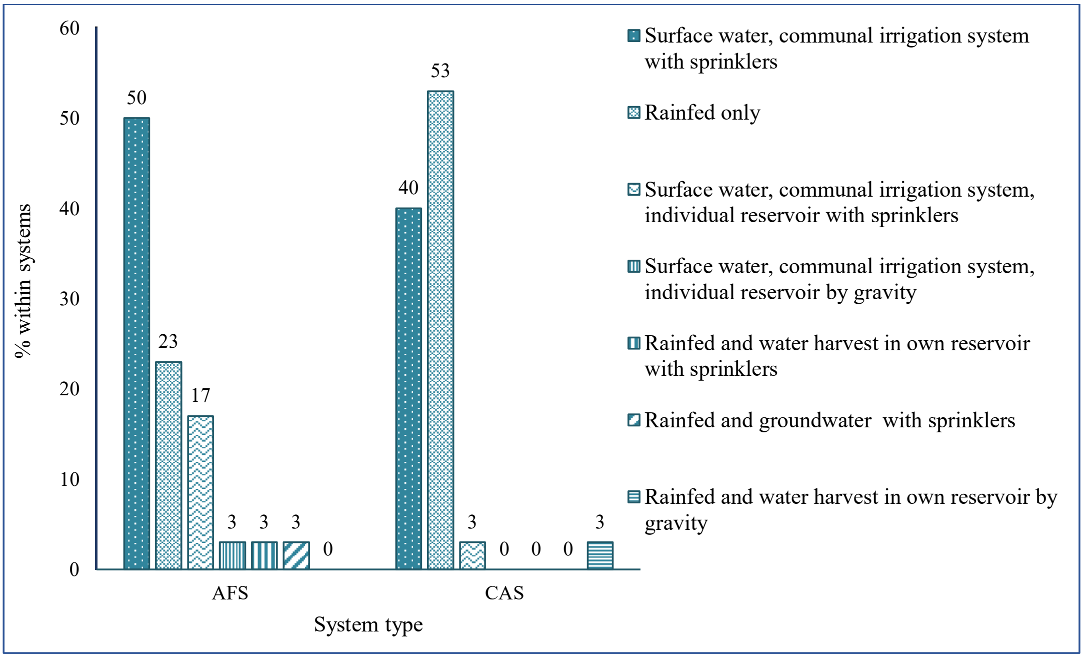


Figure 14. Main irrigation sources categorisation (modified based on Figure 7 in Study I (Córdova et al. 2018)).

4.3. Vulnerability to climate change and climatic variability of agroforestry and conventional farming systems (Studies II & III)

4.3.1. Main climate and climate-related stressors influencing the exposure of agroforestry and conventional farming systems (Study II)

The results of Table 1 show the farmers' perceptions and projections of the main gradual climate changes, extreme events, and other climatic and climate-related events that affect the farming systems during the last and forthcoming decades. The perceptions of gradual temperature and precipitation changes during the last decade and the projection for the next decade, were similar between agroforesters and conventional farmers, indicating a clear perceived annual increase of temperature and reduction in precipitation. Similar changes in temperature and precipitation were perceived during the wet/rainy and dry seasons.

The perceptions of extreme climatic events also denoted a similar tendency in both agroforesters and conventional farmers, suggesting reductions of heavy rainfall and hail events, and increases of heavy windstorms, droughts/dry periods, heat waves/warm periods and cold periods/frost.

In the case of all the other climatic and climate-related stressors, agroforesters and conventional farmers perceived stable conditions (not changes). It is important to emphasise that all farmers' perceptions about gradual climate changes, extreme events, and other climatic and climate-related events for the forthcoming decade followed the similar tendencies described above for the past decade.

Table 1. Farmers' general perceptions on gradual climate changes, extreme events, and other climatic and climate-related events (responses in % of households) (modified based on Table 1 in Study II (Córdova et al. 2019)).

	Observed by Farmers Last Decade						Expected by Farmers Next Decade					
	AFS φ			CAS φ			AFS φ			CAS φ		
Gradual Climate Changes	<	=	>	<	=	>	<	=	>	<	=	>
					Temperature							
Annual temperature	0	0	100	0	0	100	0	0	100	0	0	100
Wet/rainy season	17	17	67	20	20	60	7	3	90	7	3	90
Dry season	3	0	97	3	0	97	0	0	100	0	0	100
					Precipitation							
Annual rainfall	93	7	0	100	0	0	97	3	0	100	0	0
Wet/rainy season	93	7	0	97	3	0	97	3	0	100	0	0
Dry season	93	3	3	97	0	3	93	3	3	100	0	0
Extreme Climatic Events												
Heavy♦ rainfall events	73	13	13	83	10	7	83	7	10	83	7	10
Heavy hail events	73	17	10	87	13	0	70	20	10	87	13	0
Heavy windstorms	17	7	77	13	13	73	13	13	73	7	17	77
Droughts/dry periods	17	3	80	3	0	97	17	3	80	8	2	90
Heat waves/warm periods	13	0	87	3	0	97	10	0	90	0	0	100
Cold periods/frost	13	30	57	10	17	73	10	27	63	0	17	83

Gradual Climate Changes	Observed by Farmers Last Decade						Expected by Farmers Next Decade					
	AFS φ			CAS φ			AFS φ			CAS φ		
	<	=	>	<	=	>	<	=	>	<	=	>
Other Climatic and Climate-Related Stressors												
Glacier retreat	0	90	10	0	67	33	0	90	10	0	67	33
Thunderstorms	10	80	10	10	60	30	10	87	3	7	83	10
PWD outbreaks	7	70	23	0	83	17	7	70	23	0	83	17
Fog	3	96	0	0	100	0	7	90	3	3	77	20
Floods	3	93	3	0	100	0	3	93	3	0	100	0
Fires	7	80	13	0	100	0	7	80	13	0	100	0

♦ Heavy intensity, φ N=30

In complement to the farmers' perceptions on general exposure to CCV shown in Table 1, farmers identified the tendency of change and prioritised[23] the main climatic and climate-related stressors (CCRS) that affect their farming systems (Table 2). Farmers identified seven tendencies and CCRS distributed in 12 categories. The exposure complexity of each category is defined by the number of CCRS identified and prioritised. Therefore, a farming system with less CCRS could be seen as less exposed and vice versa. In that sense, most of conventional farmers (67%) perceived that their farming systems are exposed to five to six CCRS, while only 17% of agroforesters indicated the same kind of exposure and CCRS. On that basis, CAS tend to be greater exposed to the incidence of more CCRS than AFS. Furthermore, the analysis of specific incidence[24] (in percentage) of each CCRS identified by farmers in Table 2, indicated that agroforesters and conventional farmers have similar perception levels (100%) of the tendency related to temperature increase and rain reduction. On the other hand, conventional farmers perceived greater exposure in the incidence of droughts (20%), solar radiation (43%) and PWD outbreaks (40%) than agroforesters.

Table 2. Farmers' perceptions of main climate and climate-related stressors affecting AFS and CAS (responses in % of households) (modified based on Table 2 in Study II (Córdova et al. 2019))

Main Climatic and Climate-Related Stressors	Perceptions (%)	
	AFS φ	CAS φ
Climatic and climate-related stressors categories		
>Temperature < Rains	17	0
>Temperature < Rains > Droughts	17	7
>Temperature < Rains > Solar radiation	10	7
>Temperature < Rains > Cold periods/Frost	13	3
>Temperature < Rains >Droughts > PWD outbreaks	13	7
>Temperature <Rains >Solar radiation >Droughts	13	10
>Temperature < Rains > Solar radiation > Droughts > Winds	7	7
>Temperature < Rains > Solar radiation > Droughts > PWD outbreaks	7	40
>Temperature < Rains > Solar radiation > Cold periods/Frost > PWD outbreaks	0	3
>Temperature <Rains > Solar radiation > Droughts > Cold periods/Frost	3	7
>Temperature < Rains > Solar radiation > Cold periods/Frost > Winds > PWD outbreaks	0	7
>Temperature < Rains > Solar radiation > Droughts > Cold periods/Frost > PWD outbreaks	0	3

[23] From the most to the least influential stressor.

[24] Calculated by summing the partial percentages where the specific stressor appear in the respective category.

Main Climatic and Climate-Related Stressors	Perceptions (%)	
	AFS ᵠ	CAS ᵠ
Specific incidence of main climatic and climate-related stressors ♦		
>Temperature	100	100
<Rains	100	100
>Droughts	60	80
>Solar radiation	40	83
>PWD outbreaks	20	60
>Winds	7	13
>Cold periods/Frost	17	23

♦ Sum of partial perceptions (%) where the climate stressor appears in the correspondent category, ᵠ N=30

Furthermore, to evaluate whether or not the farmers' perceptions on temperature and precipitation changes are aligned with the changes registered by science, the Mann–Kendall test and Sen's slope estimations was conducted. Results of the test, shown in Appendix B of Study II (Córdova et al. 2019), indicate that there are not clear trends (not reductions or increases) in temperature and precipitation in the study area . Only in the precipitation measurements at Cayambe station did the test and estimations indicate an upward trend (at 0.05 level of significance), coinciding with the scientific observations of increases on precipitation observed/predicted for the Tropical Andes Region, and differing with farmers' perceptions in this study which indicate reductions in precipitation.

4.3.2. Biophysical controlling factors influencing the farming systems' sensitivity to impacts of the main climate and climate-related stressors (Study II)

Table 3 summarises the importance of the applied farming system approaches (AFS and CAS) in controlling the impacts of CCRS (described in Table 2) on the main biophysical components of the system (soil; water and biodiversity). Farmers qualified the importance of the farming approach based on a three-level scale: level 1 when the controlling capacity of the systems was less important or with little extent, level 2 for important or medium extent, and level 3 for very important or a large extent controlling capacity. Pearson Chi-square results summarised in Table 3 (and in more detail in Annex 9) indicated clear statistically significant differences ($p \leq 0.001$) among all controlling capacity estimations between agroforesters and conventional farmers. Agroforesters considered that their farming approach[25] plays a very important role controlling the deterioration of the main system's biophysical components. Between 71–88% of agroforesters indicated that the implementation of agroforestry in highlands represented a very important approach (controlling level 3 in Table 3 and in Annex 9) to control the different types of soil erosion caused by water and wind, the chemical and physical soil deterioration, and the biological and water degradation of their farming system. In contrast, a lower proportion of conventional farmers (7–25%) indicated that their farming approach[26] was very important to control the biophysical deterioration. Moreover, the majority of conventional farmers (39–60%) considered that their current farming approach was less important to control the system's biophysical degradation (controlling level 1 in Table 3 and in Annex 9).

[25] Characterised by the incorporation of trees/shrubs and based on agroecological practices.

[26] Dominated mainly by monocrops and pastures with limited implementation of agroecological practices.

Table 3. Summary of the main biophysical controlling factors influencing farming systems' s ensitivity to main climate and climate-related stressors impacts (modified based on Annex 9).

Biophysical Controlling Factors	Controlling Level Perceptions (%)						Pearson Chi-Square	
	AFS φ			CAS φ			Asymp.Sig. (2-sided)	Significance
	1	2	3	1	2	3		
Controlling soil erosion by water †	2	16	82	68	25	7	0.000	****
Controlling soil erosion by wind /reduction in wind speed	0	17	83	60	23	17	0.000	****
Controlling chemical soil deterioration †	12	10	78	51	32	17	0.000	****
Controlling physical soil deterioration †	6	17	77	48	38	13	0.000	****
Controlling biological degradation †	4	8	88	39	36	25	0.000	****
Controlling water degradation †	9	20	71	59	32	9	0.000	****

φ N = 30, † Mean among the corresponding controlling factors in Annex 9, 1 = Less important/little extent, 2 = Important/medium extent, 3 = Very important/large extent, **** ≤ 0.001.

4.3.3. Sensitivity of the farming systems' socioeconomic, cultural, and ecological processes and attributes to the impacts of the main climate and climate-related stressors (Study II)

The sensitivity analysis of the biophysical components of smallholders' farming systems, summarised in Table 3, was complemented with the analysis of on-site and off-site impacts [27] caused by the main CCRS among the socioeconomic, sociocultural and ecological components, processes and attributes (Tables 4 and 5). Farmers qualified the impacts also using a scale where: < meant a deterioration/decrement of the process/attribute; = represented no change or no impact; and > indicated an increment/improvement.

Table 4. On-farm impacts: perceptions of the main climatic and climate-related stressors affecting the socioeconomic; sociocultural and ecological functionality of AFS and CAS (modified based on Table 4 in Study II (Córdova et al. 2019)).

Farming Systems' Components, Processes, and Attributes	Impact Level Estimations (Mean %)						Pearson Chi-Square	
	AFS φ			CAS φ			Asymp. Sig. (2-sided)	Significance
	<	=	>	<	=	>		
Socioeconomic component								
Crop yield	47	47	7	83	17	0	0.009	***
Fodder production	43	50	7	90	7	3	0.001	****
Fodder quality	47	43	10	93	3	3	0.000	****
Animal production	47	50	3	83	17	0	0.010	***
Wood production	23	53	23	57	37	7	0.020	**
Risk of production failure	13	47	40	30	10	60	0.006	***
Drinking/household water availability/quality	60	33	7	87	13	0	0.049	**
Irrigation water availability/quality	40	60	0	63	37	0	0.071	*
Demand for irrigation water	3	17	80	0	17	83	0.600	NS
Expenses on agricultural inputs	17	70	13	10	30	60	0.001	****
Farm income	27	43	30	70	30	0	0.000	****
Diversification of income sources	13	53	33	43	47	10	0.013	***
Production area (new land under cultivation/use)	7	83	10	10	73	17	0.640	NS
Labor constraints	37	53	10	33	40	27	0.236	NS
Workload	10	60	30	3	27	70	0.008	***
Difficulty of farm operations	3	83	13	0	37	63	0.000	****
Product diversification	13	63	23	47	43	10	0,016	**
Sociocultural component								
Cultural opportunities (e.g., spiritual, aesthetic, others)	47	37	17	77	23	0	0.018	**
Recreational opportunities	20	70	10	50	47	3	0.044	**
Community institution strengthening	17	30	53	17	27	57	0.956	NS

[27] At farm and landscape level respectively.

Farming Systems' Components, Processes, and Attributes	Impact Level Estimations (Mean %)						Pearson Chi-Square	
	AFS φ			CAS φ			Asymp. Sig. (2-sided)	Significance
	<	=	>	<	=	>		
Traditional/Indigenous knowledge conservation	17	67	17	57	33	10	0.006	***
Conflicts	0	13	87	0	20	80	0.488	NS
Position of socially and economically disadvantaged groups (gender, age, status, ethnicity, etc.)	30	50	20	37	60	3	0.132	NS
Food security/self-sufficiency (dependence on external support)	23	63	13	60	37	3	0.012	**
Health	67	20	13	90	7	3	0.089	*
Ecological component								
Water quantity	50	40	10	93	7	0	0.001	****
Water quality	47	47	7	93	7	0	0.000	****
Harvesting/collection of water	43	47	10	90	10	0	0.001	****
Soil moisture	43	40	17	90	7	3	0.001	****
Evaporation	23	37	40	10	7	83	0.002	***
Surface runoff	37	50	13	40	13	47	0.003	***
Excess water drainage	47	47	7	50	27	23	0.108	*
Recharge of groundwater table/aquifer	40	53	7	80	20	0	0.005	***
Wind velocity	27	40	33	3	10	87	0.000	****
Soil cover	17	57	27	53	40	7	0.006	***
Biomass/above ground C	17	77	7	57	43	0	0.003	***
Nutrient cycling/recharge	20	67	13	63	33	3	0.003	***
Soil organic matter/below ground C	10	83	7	57	43	0	0.000	****
Emission of carbon and greenhouse gases	43	37	20	7	33	60	0.001	****
Soil loss	27	57	17	7	30	63	0.001	****
Soil crusting/sealing	13	70	17	7	33	60	0.003	***
Soil compaction	13	63	23	3	20	77	0.000	****
Salinity	13	80	7	3	50	47	0.002	***
Fire risk	13	63	23	0	67	33	0.103	*
Animal diversity	40	37	23	87	7	7	0.001	****
Plant diversity	37	40	23	83	10	7	0.001	****
Invasive alien species	3	83	13	10	13	77	0.000	****
Beneficial species (predators, earthworms, pollinators)	23	47	30	87	7	7	0.000	****
Biological pests/diseases	10	57	33	0	10	90	0.000	****
Habitat diversity	23	47	30	93	3	3	0.000	****

φ N = 30, <: Decreased/deteriorated, =: No impact, >: Increased/Improved, NS >0.1, * ≤0.1, ** ≤0.05, *** ≤0.01, **** ≤0.001.

The Chi-square analysis of on-farm impacts shown in Table 4 indicate a statistically difference between farming systems at different significance levels ($p \leq 0.1$, 0.05, 0.01 and 0.001). Most agroforesters reported that the socioeconomic, sociocultural, and ecological processes and attributes of their systems were not impacted by the CCRS, showing in many cases greater positive influence tendencies than in the case of conventional farmers. In contrast, conventional farmers perceived mostly a negative influence of the CCRS on the socioeconomic, sociocultural and ecological functionality of their systems.

Among socioeconomic processes and attributes, agroforesters perceived no impacts while conventional farmers perceived negative influence and impacts on their crop yield; fodder production and quality; animal and wood production; risk of production failure; irrigation water availability/quality (weak evidence, $p \leq 0.1$); expenses on agricultural inputs; farm income; diversification of income resources; workload; difficulty of farm operation; and product diversification. Conventional farmers also indicated a greater reduction of drinking/household water availability/quality than agroforesters ($p \leq 0.05$). Furthermore, perceptions on the demand for irrigation water, production area[28] and labour constraints show no significant differences between systems ($p \geq 0.1$). Therefore, both agroforesters and conventional farmers perceived that the

[28] The necessity of extra farmland area.

demand for irrigation water have increased, while the necessity for new production areas and the situation of labour constraints have not been impacted by the CCRS.

Results of the sociocultural component indicated that conventional farmers perceive a greater negative influence of the CCRS on their cultural and recreational opportunities ($p \leq 0.05$), conservation of traditional/indigenous knowledge ($p \leq 0.01$) food security/self-sufficiency ($p \leq 0.05$) and household health (weak evidence, $p \leq 0.1$). In addition, both agroforesters and conventional farmers have similar perceptions ($p \geq 0.1$) that stressors have increased conflicts[29]. At the same time these conflicts have positively influenced community institutions due to the greater unification within community members to negotiate water access and use issues with other communities and users. In addition, the impacts of CCRS on the position of socially and economically disadvantaged groups (gender, age, status, ethnicity, etc.) did not show any impact on either system types ($p \geq 0.1$).

The results of ecological component in Table 4 emphasises the positive perceptions of the majority of agroforesters for most of the ecological attributes and processes ($p \leq 0.1$, 0.05, 0.01, 0,001), while conventional farmers perceived mostly negative effects. Some interesting ecological processes and attributes to take into consideration in the CCV context could be the lack of impacts and the negative effects perceived by agroforesters and conventional farmers respectively on water quantity and quality; soil moisture; evaporation; wind velocity; soil cover; emission of carbon and greenhouse gases; soil loss, crusting/sealing and compaction; animal and plant diversity; invasive alien and beneficial species (predators, earthworms, pollinators); biological pest and diseases; and habitat diversity.

In the case of off-site impacts (at landscape level), perceptions of agroforesters and conventional farmers shown in Table 5 did not indicate statistically significant differences ($p > 0.1$). CCRS have impacted negatively on water availability (groundwater, springs); stream flow in dry season; groundwater/river pollution; buffering/filtering capacity (by soil, vegetation, wetlands); and wind transported sediments. In contrast; agroforesters and conventional farmers perceived positive impacts on the reduction of downstream flooding and sediment yield. Finally, perceptions of damage to neighbours' field and damage of public/private infrastructure did not indicate any impacts. The only process at the landscape level that has a statistically significant difference between systems, albeit with weak evidence ($p \leq 0.1$), was downstream siltation, where conventional farmers perceived more reductions in downstream siltation than agroforesters.

[29] Especially for the control and supply of drinking and irrigation water.

Table 5. Off-site impacts: perceptions of the main climatic and climate-related stressors affecting the socioeconomic, sociocultural and ecological functionality of AFS and CAS at the landscape level (modified based on Table 5 in Study II (Córdova et al. 2019)).

Processes and Attributes at landscape level	Impact Level Estimations (Mean %)						Pearson Chi-Square	
	AFS ᵠ			CAS ᵠ			Asymp. Sig. (2-sided)	Significance
	<	=	>	<	=	>		
Water availability (groundwater, springs)	100	0	0	97	3	0	0.313	NS
Downstream flooding	93	7	0	97	3	0	0.554	NS
Stream flow in dry season/reliable and stable low flows	97	0	3	100	0	0	0.313	NS
Sediment yield	83	10	7	90	0	10	0.194	NS
Downstream siltation	57	43	0	80	20	0	0.052	*
Groundwater/river pollution	7	13	80	7	0	93	0.116	NS
Buffering/filtering capacity (by soil, vegetation, wetlands)	83	13	3	93	7	0	0.399	NS
Wind transported sediments	13	27	60	3	13	83	0.118	NS
Damage on neighbors' field	3	83	13	7	90	3	0.331	NS
Damage on public/private infrastructure	10	83	7	3	87	10	0.543	NS

ᵠ N = 30, <: Decreased/deteriorated, =: No impact, >: Increased/Improved, NS > 0.1, * ≤ 0.1.

4.3.4. Adaptive capacity of smallholder farmers (Study III)

4.3.4.1. Main socioeconomic assets for adaptation (Study III)

The Pearson Chi-square analysis of the socioeconomic assets for adaptation considered in this study (Table 6) indicated no statistically significant differences ($p \geq 0.1$) for most of the assets between systems. Agroforesters and conventional farmers perceived similar advantages and constraints on their socioeconomic opportunities, social environment, information access, and other resources. Most of the socioeconomic opportunities for both agroforesters and conventional farmers were limited, indicating low off-farm income and remittance, or other income at household level, medium and low access to markets and loans. Off-farm income is normally earned from agricultural labour on other farms, flower plantations, or as construction workers in the nearby cities (in the case of men). No remittances were received by farmers in our sample, with the extra household income coming mainly from pensions of the rural social security system. Moreover, only in the case of on-farm income did agroforesters perceive that their households received better income than conventional farmers, although the statistical significance was still weak ($p \leq 0.1$).

Farmers also had limited access to markets and loans. Many agroforesters mentioned that they commercialise their products through their membership of a farmer association, having better access to local and national markets. Usually conventional farmers do not belong to an association and used to commercialise their products in more independent ways. In the case of loans, farmers mentioned that regular loan options are available from public and private institutions[30], but the accessibility was difficult due to the high interest rates and the demanding socioeconomic requirements and guaranties requested by the credit institutions[31]. For these reasons many farmers interviewed in this study preferred small loans from local credit mechanisms and local cooperatives.

[30] Such as the Development National Bank, private banks, cooperatives and local credit mechanisms (women and farmers' associations).

[31] e.g. own the land, buildings; machines, vehicles, have guarantors, age limits, etc.

Table 6. Perception levels of the main socioeconomic assets for adaptation between AFS and CAS (modified based on Table 1 in Study III).

Main socioeconomic assets for adaptation	Perception levels (%)						Pearson Chi-square	
	AFSᵠ			CASᵠ			Asymp.Sig. (2-sided)	Significance
	L	M	H	L	M	H		
Economic opportunities								
Financial resources from:								
On-farm income ♦	30	60	10	53	47	0	0.065	*
Off-farm income‡ at household levelᵠ	60	33	7	50	37	13	0.610	NS
Remittance/other income at household levelᵠ	97	3	0	97	3	0	1.000	NS
Loan options	37	40	23	37	40	23	1.000	NS
Access to market	23	60	17	40	53	7	0.257	NS
Social environment								
Connection to social networks (e.g. associations, village organisations)	20	50	30	43	43	13	0.098	*
Stability of social environment	7	63	30	7	77	17	0.467	NS
Legal framework supportive of adaptation	90	10	0	90	10	0	1.000	NS
Policies supportive of adaptation	90	10	0	93	7	0	0.640	NS
Clear institutional responsibilities for climate change related tasks	90	10	0	97	3	0	0.301	NS
Information access								
Access to reliable weather forecast information	90	10	0	100	0	0	0.076	*
Access to early warning systems related to climate hazards / shocks	100	0	0	97	3	0	0.313	NS
Access to education and training related to climate change (extension / advisory service)	63	37	0	90	10	0	0.015	**
Knowledge on adequate and timely adaptation in land management related to climate hazards / shocks	37	53	10	57	30	13	0.184	NS
Good communication / information sharing between land users / other stakeholders (policy makers, researchers) related to climate variability (feedback mechanism)	47	50	3	67	34	0	0.217	NS
Other resources								
Level of productive infrastructure	30	70	0	60	40	0	0.020	**
Availability of construction material and equipment	40	47	13	33	57	10	0.075	*
Availability of energy supplies	13	33	53	10	57	33	0.188	NS

ᵠ N=30; ‡ income other than from the use of cropland, grazing land, forest and mixed land (e.g. business, trade, manufacturing, industry); ♦ Based on MEW, high income > 1 MEW, moderate income = 1MEW, low income < 1 MEW; * ≤ 0.1; ** ≤ 0.05; NS = $p \geq 0.1$; L = low; M = Moderate; H = High.

The majority of perceptions on social environment assets show similar conditions for agroforesters and conventional farmers ($p \geq 0.1$). Only in the case of 'connection to social networks' did agroforesters perceive better opportunities to be more connected to social networks, such as associations and village organisations, than conventional farmers (weak evidence, $p \leq 0.1$). Agroforesters and conventional farmers perceived similar positive social environment (characterised by reduced crime and social conflicts in general), low opportunities related to the legal framework and policies to support their adaptation, and low knowledge of the role of institutional responsibilities for climate change related tasks.

Agroforesters had better access to reliable forecast information (weak evidence, $p \leq 0.1$) and to education-training related to climate change (extension/advisory service) ($p \leq 0.05$). On the other hand, both agroforesters and conventional farmers perceived similarly ($p \geq 0.1$) the low access to early warning systems related to climate hazards/shocks; moderate and low opportunities for good communication/information sharing between land users/other stakeholders (policy makers, researchers) related to climate variability (feedback mechanism); and also in the case of knowledge about adequate and timely adaptation in land management related to climate hazards/shocks.

The access to other complementary resources considered in Table 6 denoted better advantages for agroforesters in the level of productive infrastructure ($p \leq 0.05$), and in the availability of construction material and equipment (weak evidence, $p \leq 0.1$). Farmers' perceptions are similar ($p \geq 0.1$) on the availability of energy supplies (mostly electric energy and fossil fuels), showing moderate and high opportunities.

4.3.4.2. Adaptation experiences (Study III)

Table 7 describes the kind of training, knowledge, and adaptation measures received and adopted by farmers. These results also describe and prioritise the public, private, and civil society actors involved in the training and implementation of adaptation experiences adopted by farmers.

Table 7. Adaptation experiences between AFS and CAS (modified based on Table 2 in Study III).

Adaptation experiences	Perceptions (%)	
	AFS φ	CAS φ
Adaptation measures implemented to reduce vulnerability? (last 10 years)		
None	0	33
Agronomic ♦ and Vegetative ♣	0	3
Agronomic and Management †	0	23
Agronomic, Vegetative and Management	37	30
Agronomic, Vegetative, Structural ◊ and Management	63	10
Inspiration source		
None	0	10
By land users alone (self-initiative / bottom-up)	10	3
Mainly by land users supported by sustainable land management (SLM) specialists/agricultural advisors	83	67
By other land users	3	13
Mainly by input from SLM specialists/agricultural advisor	0	7
By researchers	3	0
Special training on adaptation measures		
Yes	90	77
No	10	23
If yes, training source		
National and international NGOs	3	0
Local government and national-international NGOs	7	0
Central - local government and international NGOs	7	0
Central government and national-international NGOs	3	0
National NGOs	13	3
Local organisations	17	40
Local organisations and national-international NGOs	20	7
International NGOs	3	0
Central - local government and national NGOs	3	3
Central - local government, local organisations and international NGOs	3	3
Local government-organisations and international NGOs	3	0
Local government-organisations and national - international NGOs	3	7
Research institutions	3	3
Central government, local organisations, national and international NGOs	0	3
National NGOs and local - international organisations	0	7

Adaptation experiences	Perceptions (%)	
	AFS ᵠ	CAS ᵠ
If not, knowledge source		
Own interest/experience	3	0
Own interest/experience, central government programs and research institutions	3	0
Own interest/experience and local organisations	3	3
Media	0	7
Traditional knowledge (parents/relatives)	0	13

ᵠ N=30, ♦ conservation agriculture, manuring/composting, mixed cropping, contour cultivation, mulching, etc.; ♣ tree planting, hedge barriers, grass strips, windbreaks, agroforestry, etc.; ◊ terraces, banks, bunds, constructions, palisades, etc.; † land use change, area closure, rotational grazing

During the last decade all agroforesters (100%) have implemented different adaptation measures to enhance their production system's tolerance to gradual climate changes and extreme events. Most of these adaptations/modifications (63%) included a combination of agronomic, vegetative, structural and management practices (Table 7). In contrast, only 66% of conventional farmers have modified their systems to become more resilient, mostly by implementing agronomic, vegetative and management practices (30%). It is remarkable that a significant proportion of conventional farmers (33%) did not implemented any adaptation measures.

Table 7 also indicates the sources from where or whom the farmers got inspiration to implement adaptation measures. The majority of agroforesters and conventional farmers indicated that the main inspiration source was their own initiative supported by sustainable land management specialists or agricultural advisors. Agroforesters had better access to special training on adaptation measures (90%)) compared to conventional farmers (77%).Agroforesters' special training was provided by public, private, and civil society actors, and mostly by local organisations[32], national and international NGOs. In contrast, the special training of conventional farmers was provided mainly by local organisations. In the case of agroforesters and conventional farmers who did not receive any special training in adaptation measures (10% and 23% respectively; Table 7), the main knowledge source for adaptation practices was their own interest and experience. Additionally, the contribution of traditional knowledge transmitted by parents and other relatives as a source of adaptation knowledge was more important for conventional farmers (13%) than agroforesters (0%).

4.3.4.3. Economic inputs and financial support to implement adaptation measures (Study III)

The results presented in Table 8 show a summary of the main expenditures[33] spent by farmers to implement the different adaptation measures described above (Table 7). Results showed no statistically significant difference between AFS and CAS for most of the annual inputs and materials used in adaptation. Only the "Other costs" category indicated a statistically significant difference between systems ($p \leq 0.01$). Therefore, agroforesters and conventional farmers spent similar amounts of economic resources annually to strength the adaptation of their systems, on items related to labour, equipment, construction and agricultural materials (described in more detail in Annex 10). Moreover, conventional farmers spent greater economic resources than agroforesters on the acquisition and keeping of livestock and minor animals. Table 9 indicates the main financial sources for adaptation and the proportion (in percentage) of the contribution from public, private and civil society institutions. The financial support was estimated as the amount of the total annual inputs and includes the economic value given by institutions for agricultural implements and other assets for adaptation such as tools, machines, seeds, seedlings, fertilisers, biocides, construction materials, animals, etc. (Annex 10). The results stressed that practically all the financial resources for

[32] Farmer associations and indigenous organisations.
[33] During the last year before the interview.

adaptation, invested by both agroforesters and conventional farmers, come from their own resources. Only a very marginal proportion of these resources were mostly supported by NGOs and local organisations (3.5% and 2.4% in the case of agroforesters and conventional farmers, respectively).

Table 8. Summary of the main differences in mean annual economic inputs for adaptation measures between AFS and CAS (modified based on Annex 10).

Annual inputs used for adaptation	AFS ᵠ	CAS ᵠ	t-Sig. (2-tailed)	Significance
Labour cost	4951	3901	0.212	NS
Equipment cost	392	389	0.974	NS
Construction material cost	187	50	0.313	NS
Agricultural cost	630	271	0.104	NS
Other costs ‡	286	889	0.006	***
Total cost	6446	5499	0.358	NS

ᵠ N = 30; *** $p \leq 0.01$; NS = $p \geq 0.1$; ‡ livestock, minor animals, fodder, vaccines, vitamins, inseminations, etc.

Table 9. Contribution of main financial sources to annual inputs for adaptation measures (not including credit) (modified based on Table 4 in Study III).

Main financial sources for adaptation	Contribution (%)	
	AFS ᵠ	CAS ᵠ
Own sources	90.5	94.2
Intergovernmental	0.7	0.8
Central government	0.3	0.7
International non-government	3.5	0.3
National non-government	2.5	1.1
Private sector	0.0	0.0
Local government	1.3	0.5
Local community/other farmer(s)	0.0	0.0
Local organisations	1.4	2.4

ᵠ N = 30

4.4. Summary of the key findings of the study

4.4.1. Biophysical and socioeconomic sustainability

AFS have the following characteristics compared with CAS:

- Higher levels of agrobiodiversity and uses, especially in the case of cultivated biodiversity (species, cultivars and breeds). AFS in this study tend to be more genetically diversified farming systems than CAS, suggesting better socioeconomic and environmental assets of these systems to sustain agroforesters' livelihoods and households.
- More diversified livelihood portfolios based on on-farm activities, self-consumption and commercialisation of diversified farm products. These aspects in the context of global change

represent important advantages to manage and decrease socioeconomic and environmental vulnerabilities and risks.

- Better land tenure security, which could enhance farmers' opportunities and motivation to invest in assets for production (infrastructure, technology, trees, crops, animals, irrigation systems).
- Higher on-farm incomes levels and less dependence on off-farm activities for economic income generation.
- More diversified irrigation sources and less dependency on rainfall, being less vulnerable to climate variability and change (water shortages and droughts).

On the other hand, AFS and CAS show similarities in the following characteristics:

- Soil fertility conditions.
- Microclimate conditions inside farm

N.B. similar soil fertility and microclimate conditions may be due to the small sample used.

4.4.2. Vulnerability to climate change and variability

Exposure:

- Increases in temperature and reductions in precipitation are similarly perceived by both agroforesters and conventional farmers for the past and next decade.
- Conventional systems tend to be more exposed to solar radiation (43%), pests, weeds and disease outbreaks (40%), and droughts (20%), than agroforestry systems.

Sensitivity:

- Most agroforesters consider that their farming approach (characterised by the incorporation of trees/shrubs to the system, based on agroecological principles), is very important to control the deterioration of the main biophysical components of the system such as soil, water, and biodiversity.
- Most agroforesters indicate that CCRS (>Temperature, <Precipitation, >Solar radiation, >Droughts, >Frost, > Winds, > PWD outbreaks), do not influence the functionality of their systems either positively nor negatively (i.e. no impacts); whereas conventional farmers mostly consider that CCRS negatively influence the functionality of their systems.

Adaptive Capacity

- Both agroforesters and conventional farmers in general reported having low and moderate socioeconomic adaptive capacity opportunities; a shortcoming that could increase their vulnerability to climate change, variability, and extremes.
- Agroforesters show better adaptive capacity than conventional farmers in aspects related to: better connections to social networks; more access to reliable weather forecast information; better access to education and training related to climate change; higher levels of productive infrastructure; and greater implementation of agronomic, vegetative, structural and management adaptive measures.
- Agroforesters also reported having better knowledge and experience to support autonomous adaptation.

- Local/indigenous organisations have a key role supporting farmers' adaptive capacity.
- The contribution of public, private and civil society institutions is marginal (almost non-existing), especially in training and financial support to implement adaptation measures. Smallholder farmers, at least in this study, are basically dealing with climate change and variability alone.

5. Discussion

5.1. Main sustainability and vulnerability factors influencing agroforestry and conventional farming system's adaptation to climate change, variability, and extreme climatic events

5.1.1. Biophysical and socioeconomic factors

Most biophysical and socioeconomic results taken into account in this study to evaluate the sustainability of smallholder farming systems indicate that AFS have more assets and opportunities to support sustainable farming systems and livelihoods.

In terms of agrobiodiversity, the higher levels of cultivated and associated biodiversity in AFS could represent an important advantage to sustain rural livelihoods and maintain key farming system services. A large body of literature has emphasised the importance of agrobiodiversity in supporting sustainable food systems through the provision of diversified foods to improve diets and reduce malnutrition (Thrupp 2004, CBD 2008, de Boef et al. 2016, Leakey 2017); a major problem in the highlands and in the ITKP (The World Bank 2007, Velasco et al. 2018). It is also known that higher levels of agrobiodiversity in a production system could maintain important provisioning and regulatory ecosystem services (e.g. pollination; pest and disease control, microclimate; primary production; yield efficiency and stability; habitats and nutrients provision; and enhance water cycling). In the global change context, the higher levels of agrobiodiversity found in AFS could provide better socioeconomic and environmental opportunities for the sustainability of smallholder agroforesters' livelihoods, enhancing also the natural capital of the system (natural resource base), as stressed in an increasing body of publications (Chambers and Conway 1992, Sconnes 1998, Pascual et al. 2011, Zimmerer and Vanek 2016). The higher number of cultivars and breeds contained in AFS also represents an important advantage to enhance the adaptation of agroforesters. Particularly, the greater availability of cultivars constitutes an in-situ genetic bank and may contain potential cultivars more adaptable and resilient to the expected CCV impacts in the Tropical Andes (drier/warmer conditions and higher incidence of PWD outbreaks on main crops and livestock, affecting their productivity) (Magrin et al. 2014, Porter et al. 2014, Roy et al. 2018, IPCC 2019b, Shukla et al. 2019). The benefits of higher levels of agrobiodiversity in AFS, in particular for cultivated biodiversity, are also evidenced in the greater use of subsistence/functional and commercial species (Figure 12 and Annex 8). Therefore, the greater availability and use of subsistence-functional species by agroforesters, could better support their food security/sovereignty, a permanent risk reported in the ITKP (Velasco et al. 2018). In addition, the greater use of commercial species by agroforesters represents an important advantage for the diversification of their economic incomes, supporting also their financial-economic capital. Other studies conducted in other Ecuadorian highland regions also report high levels of agrobiodiversity in smallholding systems (Oyarzun et al. 2013). These authors indicate that the numbers of on-farm cultivated species and species and products used for home consumption are positively related. Oyarzun et al. (2013) suggest that smallholder households with low agrobiodiversity levels usually consume less on-farm foods than households who keep more agrobiodiversity in their farms. In this study the findings of the main agrobiodiversity usages coincide with findings of other studies suggesting that smallholder farmers in Ecuadorian highlands dedicate the majority of their production to family consumption and fulfilling subsistence needs[34] (Chiriboga 1982, Wong and Ludeña 2006, Bravo et al. 2016).

Despite numerous studies reporting the biophysical benefits of agroforestry practices in maintaining and improving soil fertility and microclimate conditions (Young 1985, Boelee 2011, van Noordwijk et al. 2014, Barrios et al. 2018, IPCC 2019b, Mbow et al. 2019, Olsson et al. 2019, Shukla et al. 2019), most of the results of soil fertility and microclimate in this study did not show differences between AFS and CAS. This may be due to the small sample size used to evaluate the parameters of soil fertility and microclimate. Although there were no statistically significant differences among the microclimate parameters between agroecosystems, it is important to remark again that in mountain farming systems even small fluctuations in microclimate, and particularly changes in humidity and temperature, could affect the viability of a variety of crops (Price 1995, Zimmerer 1999, Beniston 2003). In that sense, the warmer and more stable temperature conditions registered in AFS could be considered as interesting microcline conditions to avoid, for example, frost, cold, and variations in temperature that usually negatively influence the production of farming systems in highlands and the suitability of species, cultivars and breeds.

Although the livelihood portfolio composition[35] of agroforesters and conventional farmers[36] denotes some similar characteristics, there are some differences related to on- and off-farm activities that could influence the sustainability of livelihoods. Firstly, the more diversified livelihood portfolios of agroforesters could play an important role reducing their socioeconomic and environmental vulnerability and risk, especially in the context of global change (such as market fluctuations, disease, natural hazards and climate extremes), due to the more dynamic and varied set of activities included in their livelihood portfolios. Secondly, off-farm livelihood activities of agroforesters are complemented with on-farm activities mainly oriented to support and enhance their cash incomes and food security (e.g. off-farm work complemented with dairy farming + farm product commercialisation + subsistence farming) (Figure 10). On the other hand, complementary on-farm activities included in the livelihood portfolios of conventional farmers are mainly related to the production of staple crops for family consumption (subsistence farming). In that sense, agroforesters' off-farm portfolio composition shows greater opportunities to support sustainability than in the case of conventional farmers, due to its potential to provide extra financial support to agroforesters' capital component through an array of complementary cash income activities. Usually the off-farm portfolios of smallholder farmers include an array of activities to support extra cash income (Hussein and Nelson 1998, Ellis 2000). Permanent or temporary migration of some household members (mainly men and youths) to work in cities is the most common strategy to diversify the livelihoods of smallholder farmers, especially in developing countries (Hussein and Nelson 1998, Sconnes 1998, Ellis 2000, Zimmerer and Vanek 2016). It is important to remark that in this study the off-farm livelihood activities were also characterised by temporary or permanent migration, especially of men, to find better work opportunities usually in the construction industry as labourers, or in the case of women in the expanding fresh-cut flower sector (Newman et al. 2002, Vega and Philhower 2009, Conefrey 2015, Ávalos 2017, Knapp 2017, Martínez 2017). Furthermore, the higher dependence on off-farm activities and incomes by conventional farmers in this study are aligned with results of other studies (especially in the case of Ecuadorian Highlands)

[34] Fodder, seed conservation, small scale commercialisation.

[35] Prioritised by farmers considering first the activity with a highest cash income to the lowest one.

[36] The main activities carried out by farmers in order to support/improve their incomes and reduce socioeconomic and environmental risks.

(Martínez 2013), but differs in the case of agroforesters whose livelihoods are less dependent on off-farm activities and incomes.

Regarding land tenure, the differences between farming systems in this study also provide interesting elements in the sustainability discussion. To date, various studies suggest that land tenure status represents a transcendental condition to enhance or constrain the sustainability and adaptation of smallholder farmers, and overall mitigation (Dasgupta et al. 2014, Roy et al. 2018, IPCC 2019b, Shukla et al. 2019). The more secure land tenure shown by agroforesters in this study could be a key factor to improve the investments and adoption of SLM practices (evidenced also in Section 4.3.4.2 and Table 7 in this study) , avoid and reduce land degradation, increase production and economic benefits, maintain agrobiodiversity, facilitate innovation and upgrade technology, encourage decision making, enhance food security/land governance and policy, and ensure the rights to water for agriculture or livestock (Roy et al. 2018, Hurlbert et al. 2019, Mbow et al. 2019, Olsson et al. 2019, Shukla et al. 2019). Moreover, farmers with insecure land tenure (such as most of the conventional farmers in this study), could have limitations accessing the socioeconomic, environmental and institutional benefits mentioned above, being also more vulnerable due to the risk of their property rights from potential land claimants or even through eviction (FAO 2002). In general, insecure land tenure could increase vulnerability and decrease the adaptive capacity of farmers, limiting their access rights to water and land, reducing food security and sovereignty, and limiting the investments in key productive assets e.g. farm equipment and infrastructure, irrigation systems, credit, financial assistance and technology. Land tenure insecurity could also restrict the implementation of SLM approaches and practices such as agroecology, agroforestry, sustainable intensification, climate-smart agriculture, terracing, traditional integrated watershed management, conservation and organic agriculture, diversification, integrated pest management, rain water harvesting, conservation of pollinators, precision agriculture, etc. (Hurlbert et al. 2019, IPCC 2019b, Olsson et al. 2019, Shukla et al. 2019). The results of this study provide a good example of the importance of secured land tenure in adaptation and mitigation processes. The vulnerability of AFS to CCV is most likely reduced due to the better access to water, greater diversification of irrigation sources and the low dependence on rainfed, which also has a positive influence on the productivity of the system. Moreover, the sustainability of agroforesters' livelihoods in this study could be enhanced by their better land tenure status. Clear property rights is a great motivation to implement sustainable production approaches/practices and invest in productive assets[37]. These conditions could enable farmers to diversify and intensify the agricultural activities that enhance the self-sufficiency of their livelihoods, focused on achieving economic and food-security/sovereignty. Key biophysical and socioeconomic findings of this study coincide with previous studies that consider agroforestry to be one of the land use approaches and practices showing high potential to support and enhance sustainable livelihoods and the adaptation of smallholder farming systems, and also having a an important potential for CCV mitigation[38] (Watson et al. 2000, Selvarajh-Jaffery et al. 2007, Lasco et al. 2014, van Noordwijk et al. 2014, Zomer et al. 2014a, Roy et al. 2018, Hurlbert et al. 2019, Mbow et al. 2019, Olsson et al. 2019, Shukla et al. 2019).

5.1.2. Exposure

Agroforesters and conventional farmers in this study clearly perceived temperature increases in all seasons throughout the year, both for the last decade and the next decade to come. These perceptions are aligned with documented observations and projections based on different climate change

[37] Trees for agroforestry practices, increment on agrobiodiversity, improvements to farm equipment and infrastructure; and implementation of irrigation systems.

[38] Through fixation and being semi/permanent above-below sinks of GHG, especially CO_2 and NH_4.

scenarios for Northern and Tropical Andes (Vuille et al. 2008, Urrutia and Vuille 2009, Magrin et al. 2014, Magrin 2015, Reyer et al. 2017). Furthermore, both agroforesters and conventional farmers perceived reducing precipitation throughout the year, for both the last decade and the next decade to come. These perceptions differ from observed and projected precipitation changes in the Andean region. Observations and projections of precipitation indicate increases in precipitation for the last decade and the next decade to come (Haylock et al. 2006, Vuille et al. 2008, Urrutia and Vuille 2009, Buytaert and Ramírez-Villegas 2012). Moreover, several studies present evidence of decreases in precipitation and increases in temperature in Ecuadorian Northern Andes and areas around the equator during the last decades (5% to 20% and +1.4 to +2.4 C°, respectively) (Mejía et al. 1998, Palacios and Céceres 1998, Muñoz 2010, Jiménez et al. 2012). The differences among observations and projections, especially in the case of precipitation changes along Northern Tropical Andes indicated above, could respond to the internal variability/seasonality of the different microclimates along the Northern Tropical Andes, influenced also by yearly and decadal variation of El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Buytaert et al. 2010, Schoolmeester et al. 2016). In that sense, the Mann–Kendall test and Sen's slope estimations conducted in this study indicate that there are not clear trends in temperature and precipitation changes, as reported in Study II (Córdova et al. 2019). Therefore, the trends perceived by farmers in this study (increases in temperature and reductions in precipitation) could be related to inter-annual variability (climatic variability between the years) or to the intra-annual variability (between the seasons), and may not to climate changes, as it is observed in the inter-annual and intra-annual variability on precipitation in Appendix B (Figure A2 a,b, Figure A3 a,b, and Figure A4 a,b) of Study II (Córdova et al. 2019). The lack of clear temperature and precipitation trends for most of the available time series in the study area may be due to the very limited and fragmented official data available that reduce the accuracy of the Mann–Kendall test and Sen's slope estimations.

Regarding the findings about perceptions of extreme climate events (ECE), agroforesters and conventional farmers had similar trends with interesting coincidences and differences when compared with the observed and projected trends according to scientific sources. The perceived reduction in heavy rainfall events are, for example, in line with observations and projections reported in many Andean region studies (Donat et al. 2013, Magrin et al. 2014). These reductions may be related to the farmers' perceptions of annual and seasonal precipitation reductions as indicated above. Farmers also perceived reductions in hail events, which could be considered as a positive change since hail events are one of the most unpredictable and destructive weather events for crops. Comparing the farmer's perceptions of hail events to official/scientific measurements is a complicated task, mainly due to the lack long-term and consistent observations in the study area. There are, however, some studies from other regions about the influence of climate change on the frequency of hailstorm events, which show similarities with the perceptions reported in this study. For example, reductions in the frequency of hail events but increased hail damage potential due to the increase in hail size were reported and projected for some parts of North America (Brimelow et al. 2017), and reductions in hail size and events were reported over China (Ni et al. 2017). On the other hand, inner-tropics studies in the Andean region report decreases in the frequency of hail events during the last decades (Cepeda 2010), while outer-tropics studies show inconsistent trends, therefore emphasising the site-specific dependence (region, topography, altitude, latitude, longitude) of this climatic event (de la Torre et al. 2011, Mezher et al. 2012, Valdivia et al. 2013, Rasmussen et al. 2014). In addition, perceptions reported in this study about increased incidence of heavy windstorms, droughts/dry periods, and heat waves/warm periods are clearly aligned with scientific observations and projections (Donat et al. 2013, Magrin et al. 2014, Fernandez et al. 2015, Reyer et al. 2017, Schoolmeester et al. 2016), while perceptions about cold periods/frost increments differ with the robust reductions reported by scientific observations and projections (Urrutia and

Vuille 2009, Magrin et al. 2014, Magrin 2015).

Perceptions about the Cayambe Volcano glacial retreat in this study was an interesting finding. Neither conventional farmers or agroforesters perceived any important change in the Cayambe glacier mass during the last and next decade. These perceptions contradict the well-studied phenomenon of tropical glaciers retreating (especially during ENSO periods), which represents strong evidence of global warming (Vuille et al. 2007, Vuille et al. 2008, Urrutia and Vuille 2009, Francou et al. 2014, Magrin et al. 2014) In the case of the Cayambe glacier, studies report a decrease of between 25% and 48% of the glacier area during past decades (1979–2009) (Cáceres 2010, Brito 2014). The perceived lack of change in the glacier mass by most smallholder farmers interviewed in this study may be due to the absence of any noticeable or destructive events, in addition to the permanent cloudy conditions inhibiting the view of the glacier (INAMHI 2017b, INAMHI 2017a, INAMHI 2018b, INAMHI 2018a). Moreover, exposure perceptions among climate and non-climate stressors present interesting similarities and differences between farming systems. The greater exposure perceived by conventional farmers suggests that CAS could be more vulnerable to CCV than AFS. On the other hand, lower perceived exposure in AFS supports the findings of other studies, that demonstrate how farming systems based on agroecological approaches/practices - including agroforestry - are less vulnerable to the negative impacts of climate change, extremes, and other climate-related events described above, while also enhancing incremental adaptation and resilience of agricultural systems (Verchot et al. 2007, Lasco et al. 2014, van Noordwijk et al. 2014, Mbow et al. 2019, Olsson et al. 2019).

The greater exposure to solar radiation perceived by conventional farmers (mainly as heat stress during farming activities), constitutes one of the least studied climate stressors. High radiation and heat stress could have consequences in the productivity of the systems and in farmers' health (Olsson et al. 2014, Wästerlund 2018). The lower radiation/heat stress perceived by agroforesters may be explained by the favourable shade and environmental conditions provided by trees and shrubs, as part of the buffering functions of these systems (van Noordwijk et al. 2014). Ultraviolet radiation exposure and heat stress-related illnesses constitute stressors that should be taken into account more seriously in the studied area, considering the lack of studies on the impacts of these stressors in agricultural workers in the study area and worldwide, and the fact that the production systems are located in equatorial highlands (2500–3300 m.a.s.l). In this zone, the ultraviolet radiation index (UVI) is one of the highest on planet (EXA 2008, Harari Arjona et al. 2016). Farmers in this study already indicated that current exposure to stronger solar radiation and hot temperatures have increased risk situations of heat exhaustion, sunburn, and chronic effects on skin and eyes (such as photoaging, cortical cataract, and pterygium), common disorders reported in other studies and specialised literature, suggesting increases of skin cancers in the Andean region and worldwide (WHO 2002, Lucas et al. 2006, Vecchia et al. 2007, EXA 2008, Harari Arjona et al. 2016).

5.1.3. Sensitivity

Sensitivity perceptions of the main impacts of ECE and gradual climate changes in the biophysical components of the farming systems in this study (soil, water and biodiversity) denote less sensitivity in AFS than CAS. AFS clearly show better capacities to control land and soil degradation, included erosion, chemical/physical deterioration and biological and water degradation of the system (Table 3).

In that sense, the better capacity of AFS to control land and soil degradation is an important advantage to maintain soil fertility, a very basic requirement to guarantee the productivity of the system and food security of farmers' households, especially in developing countries (St.Clair and

Lynch 2010). The better land and soil controlling capacity of AFS is an important characteristic of the system, given that water and wind erosion are reported as being the most common drivers of soil deterioration worldwide, including Ecuador and the study area (de Noni and Trujillo 1986, de Noni et al. 1996, Liniger et al. 2007, Jiménez et al. 2012, Olsson et al. 2019). Additionally, land and soil degradation processes could be exacerbated by CCV and ECE (Olsson et al. 2019). In the case of the Andes and other mountain regions, observed and expected warmer conditions and changes in precipitation regimes are accelerating the decomposition of soil organic matter[39] and reduce organic matter in soils (Buytaert et al. 2011, De Bièvre et al. 2012, Olsson et al. 2019). Consequently, greater capacity of AFS to increase soil organic matter and nutrient availability/supply/recycling (Table 3), will be a significant contribution to maintaining soil fertility and reducing vulnerability to CCV. Agroforesters perceptions on greater contribution of soil organic matter and nutrient availability support the findings of other studies that show how organic and agroecological farming systems, including AFS, could contain higher soil organic matter content and lower nutrient losses per unit area than other systems (Tuomisto et al. 2012, Rossing et al. 2014, Olsson et al. 2019). Meanwhile, perceptions of physical properties of soils indicate better conditions in AFS to improve texture and structure of top/subsoil, which contributes to reducing the problems of crusting, sealing, compaction, and hardpan. The benefits of implementing agroecological practices and the incorporation of trees/shrubs in the farming systems, could be reflected in the more positive perceptions of agroforesters about soil stabilisation and infiltration properties (Table 3). The ability of AFS to reduce compaction, improve texture, structure and infiltration of top/subsoil, also contribute towards maintaining soil fertility, enhancing the physical and chemical soil processes[40], reducing wind and water erosion, and reducing GHG emissions[41], as common benefits attributed to well-structured and non-compacted soils (Horn et al. 1995, Olsson et al. 2019). Perceptions about the processes to control biological degradation in soil in the system are also more positive in AFS. Greater capacity of AFS to avoid biological degradation and promote agrobiodiversity could reduce vulnerability, maintain system functionality, enhance food security, and increase the overall systems' resilience (Thrupp 2004, CBD 2008, Pascual et al. 2011, de Boef et al. 2016).

Avoidance of biological degradation and promotion of agrobiodiversity represent transcendental processes, given that global warming and climate change are contributing to the continuing decline of biodiversity and agrobiodiversity at all spatial scales (Gitay et al. 2001, de Boef et al. 2016, Roy et al. 2018, WWF 2018, Mbow et al. 2019, Olsson et al. 2019). The greater capacity of AFS to increase beneficial species, reduce invasive alien species, and control pests (Table 3), is also an important processes to maintain yields, food security, and reduce the vulnerability and incidence of pests/diseases attacks; problems that are exacerbated by global warming and CCV (Magrin et al. 2014, Olesen 2014, Porter et al. 2014, Roy et al. 2018, Mbow et al. 2019). The lower levels of biological degradation and better promotion of agrobiodiversity perceived in AFS in thus study, could be seen and related with the greater levels of agrobiodiversity contained in these systems (Study I).

Another important process in the climate change context is the availability and capacity of farming systems to maintain water and humidity. The enhanced ability of AFS to control water degradation[42] perceived in this study constitutes a crucial advantage to reduce sensitivity and vulnerability to the

[39] One of the most important soil fertility components.
[40] e.g. mass flow, diffusion of water, ions and gases.
[41] e.g. CO_2, CH_4 and N_2O.
[42] Especially reflected in the better capacity of AFS to increase/maintain water stored in soil, improve water harvesting/collection, reduce evaporation and support water spreading (Table 3).

observed and projected warmer and dryer conditions for Tropical Andes[43](Parry et al. 2007, Urrutia and Vuille 2009, Jiménez et al. 2012, Donat et al. 2013, Magrin et al. 2014, Mbow et al. 2019). The superior water degradation control of AFS perceived in this study is consistent with other studies that indicate the greater drought resilience and soil water-holding capacity of AFS compared to other land use systems (Rossing et al. 2014).

Qualifications of on- and off –site impacts caused by the main CCRS, and how the farming approach and practices, could mitigate them (Tables 4 and 5), revealed interesting findings in relation to functionality and resilience. Most of the attributes and processes (44 of 50) included in on-site impacts (farm level), suggest more positive effects for the functionality of AFS (Table 4). On the other hand, CAS tend to be more negatively affected by CCRS, suggesting greater sensitivity than AFS. Similar tendencies were identified for most of the socioeconomic and ecological attributes and processes, being more remarkable in the case of the ecological component. The impacts of CCRS on sociocultural attributes and processes indicate less negative effects on AFS; e.g. in the case of cultural and recreational opportunities, preserving traditional knowledge, food security/self-sufficiency (dependence on external support) and health. Moreover, while conflicts had mostly negative impacts, community institutions were strengthened in response to dealing with the conflicts, which has can be seen as a positive impact. The position of socially and economically disadvantaged groups (gender, age, status, ethnicity, etc.) was not influenced by CCRS in either system types, a finding not consistent with other studies, which indicate that in most developing countries, women and young children could be particularly vulnerable to climate variability and extremes, while the elderly could be socially isolated (Dasgupta et al. 2014, Magrin et al. 2014, FAO et al. 2018). It is also reported that prevalence of severe food insecurity is higher among women, with the largest differences found in Latin America (FAO et al. 2018, Mbow et al. 2019).

The reduction in yields of major crops, both observed and projected, in low- latitude regions including the Tropical Andes is already affecting the livelihoods of smallholder farmers (Olesen 2014, Porter et al. 2014, Webber et al. 2014, Hurlbert et al. 2019, Mbow et al. 2019). Therefore, production systems that are able to maintain and improve productivity could be the most suitable systems to guarantee food security and reduce poverty of millions of smallholder households. In this context, the lower sensitivity of AFS in key socioeconomic attributes and processes related to the system's productivity and farmers' livelihoods (Table 4) represents a very important advantage to guarantee food security and reduce poverty in agroforesters' households; persistent problems intensified by CCV (Olsson et al. 2014, Hurlbert et al. 2019, Mbow et al. 2019). Taking into consideration that climate variability and extremes, especially severe droughts, are highly connected with the recent rise in global hunger, the greater socioeconomic and biophysical capacity of AFS to guarantee food security/self-sufficiency constitutes a major advantage to enhance the sustainability and reduce vulnerability to CCV in smallholders' livelihoods. Therefore, the lower exposure to droughts shown by AFS (Table 3) represents an important advantage for the resilience of these type of systems.

Regarding the impacts of CCRS in the ecological component of systems, the positive perceptions of the AFS in aspects related to water, soil, and biodiversity conservation (Table 5), could be associated with the greater biophysical controlling factors indicated also for AFS (Table 4). These findings support the worldwide assumption that AFS are one of the most promising land use management systems for water, soil (Garrity 2012, Pachauri 2012, Olsson et al. 2019) and biodiversity conservation (Leakey 2012, van Noordwijk et al. 2014, Dooley et al. 2018b). In

[43] Characterised mainly for less and more erratic precipitation, increase of temperature, evapotranspiration, and longer drought periods.

addition, the higher vulnerability shown by CAS in key water-related attributes[44] coincides with vulnerability observations and projections focused in mountains and Tropical Andes (Hatfield and Prueger 2004, Parry et al. 2007, Magrin et al. 2014, Settele et al. 2014, Schoolmeester et al. 2016).

Finally, perceptions on the sensitivity of landscape to impacts of the main CCRS (off-site impacts, Table 5), do not show differences between systems. Wind erosion is perceived differently at the farm and landscape level. Most agroforesters perceived that their farming system approach is very effective controlling wind erosion at the farm level, while conventional farmers not. On the other hand, the effects of wind erosion at the landscape level are equally perceived by both agroforesters and conventional farmers. In the context of climate change, several studies indicate that the expected dryer conditions caused mainly by increases in temperature, changes in precipitation regimes and prolonged droughts, and anthropogenic actions, could intensify wind erosion processes (Lee et al. 1996, Phillips et al. 1996, St.Clair and Lynch 2010, Olesen 2014, Settele et al. 2014, Mirzabaev et al. 2019, Olsson et al. 2019). Consequently, the better capacity of AFS to avoid and control wind erosion in this study, support the well-known potential of these systems to control wind erosion at the farm and landscape levels (Garrity 2012, Steiner 2012, Rossing et al. 2014, van Noordwijk et al. 2014, Mirzabaev et al. 2019, Olsson et al. 2019).

5.1.4. Adaptive capacity

The different adaptive capacity elements included in this study[45], represented a comprehensive set of socioeconomic, institutional and environmental factors to evaluate the assets, strategies, measures and needs of smallholder farmers in response to CCV.

The agroforesters and conventional farmers' perceptions on socioeconomic assets for adaptation were, in general, similar in regards to the socioeconomic opportunities and constraints that influence their adaptive capacity. However, there was statistical evidence on assets suggesting better capacities and opportunities for agroforesters. Both agroforesters and conventional farmers perceived that they have low and moderate opportunities of support for their adaptive capacity in regards to on/off-farm income, loan options, market access, and remittances. These low and moderate economic conditions might jeopardise the economic opportunities and sustainability of their farming systems and livelihoods. The economic vulnerability and the lack of economic opportunities is clearly visible in the high poverty and marginalisation faced by Kayambi farmers (Figure 5). Furthermore, as highlighted in other studies, the assets with more opportunities to be influenced and controlled by farmers and local community (e.g. connections to social networks, associations, village organisations) and the stability of their social environment (local safety at household and community levels), present greater positive opportunities to influence the adaptive capacity of farmers (Zhai et al. 2018). Moreover, in this study, the opportunities of access to social networks are greater for agroforesters. On the other hand, the assets that have less farmer and community influence/control, and also more dependent on external actors, (e.g. the legal framework and policies supportive of adaptation), indicate low opportunities to support the adaptive capacity of both agroforesters and conventional farmers.

The access to information related to CCV could have a key influence in the adaptive capacity of farmers and in their choices for adaptation to weather and climate (e.g. to be prepared for droughts and insect outbreaks, to improve their water harvesting techniques and livestock management) (WMO 2007, Lu 2009, WMO 2016, Singh et al. 2017). In this sense, the farmers' perceptions in

[44] Reduction in water quantity, quality, soil moisture, and increased evaporation.

[45] Based on the WCCQV2.

this study show mostly limited and moderate access opportunities for both farmer types. Although in the case of agroforesters, in particular, their access to reliable weather forecast information and education/training related to climate change might be due to the support of local organisations and national/international NGO's. In the Ecuadorian highlands - which are characterised by rapid altitudinal, diurnal and seasonal weather conditions changes (Cañadas 1983, Price 1995, Beniston 2003, Buytaert et al. 2006, Martínez et al. 2011) - access to reliable weather forecast information could represent an important advantage to improve the efficiency and management of farming activities that are susceptible to weather. Additionally, better access to weather forecast information could improve farmer's health, avoiding exposure to extreme meteorological conditions such as high solar radiation, heat waves, cold/frost periods and heavy rainfall/hail events. Furthermore, farmers with better access to education and training related to climate change (extension/advisory service), could be more aware of the impacts of CCV on their systems and households, and may have also better conditions and opportunities to implement more sophisticated adaptation measures, as is reflected in the more diversified adaptation measures applied by the majority of agroforesters (Table 7). The limited access to climatic information and climate change education/training faced by most conventional farmers may be due to their lower opportunities for social connection (farmers' associations, village and local organisations, etc.) (Table 6). Supporting institutions that provide training related to adaptation are better able to service organised groups of farmers as opposed to individuals. Therefore, farmers with more opportunities to be part of social groups and organisations might have more possibilities to access information, education and training.

Globally, public and private institutions – including local governments, non-government/civil society organisations and private sector – generally represent key actors associated with successful adaptation (Field et al. 2014, Noble et al. 2014, Jamshidi et al. 2019). In this study, the limited and moderate opportunities perceived by agroforesters and conventional farmers on the other information aspects (such as access to early warning systems, knowledge on timely adaptation in land management, and information related to climate hazards/shocks (Table 6)), denote the very marginal contribution and involvement of public and private institutions in supporting the adaptive capacity of farmers. These results are similar to findings of studies conducted in other developing regions (Jamshidi et al. 2019, Williams et al. 2019). Therefore, the adaptive capacity of smallholder farmers in this study relies mainly on their own socioeconomic and biophysical/environmental capabilities to cope and deal with global warming and CCV. The autonomous adaptation capacity shown by smallholder farmers in this study, based mainly on their experience and traditional knowledge, coincide with results found in similar studies in tropical countries (Nyong et al. 2007, Mutekwa 2009, Boillat and Berkes 2013, Quiroga et al. 2015, Makuvaro et al. 2018).

The lack of adequate mechanisms and social/institutional capital to communication/information sharing mechanisms between farmers and other stakeholders (Table 6) could limit the key role played by traditional/indigenous knowledge and social networking for successful adaptation (Alexander et al. 2011, Naess 2013, Field et al. 2014, Noble et al. 2014, Chaudhury et al. 2017, Olsson et al. 2019). This is especially the case for conventional farmers because these farmers tend to be less integrated to social networks than agroforesters (Table 6). In this context, indigenous/traditional knowledge may not be properly used to inform land users' local approaches and practices to promote successful adaptation. Moreover, the moderate and high levels of productive infrastructure (especially perceived by agroforesters), and the availability of energy supplies (similarly perceived in both systems), could have a high potential to enhance farmers' adaptation. Nevertheless, the main limitation of farmers to take advantage of these positive assets may be related to low access opportunities to these assets, mainly due to the persistent high poverty levels and marginalisation of Kayambi people. Furthermore, the better levels of productive infrastructure perceived by agroforesters may be linked to the higher access to, and diversification of irrigation systems, and more secure land tenure as perceived by the farmers who manage in these types of systems (Study I). In the case of availability of construction material and equipment, the low and moderate availability perceived by agroforesters and conventional farmers may represent an important limiting obstacle to enhance their adaptive capacity. These limitations could be more relevant in the climate change context and situations when more alternative and sustainable management practices could be needed to cope and deal with the impacts of CCV and ECE. For example, implementation of more efficient irrigation systems and water harvesting practices due to the increased frequency of dry periods/droughts and the reductions in precipitation, already perceived by farmers (Study I).

Regarding the type and conditions of adaptation measures to reduce vulnerability (Table 7), the greater adaptation measures and modifications implemented by all agroforesters during the last decade represents an important and transformative set of actions to support and enhance the resilience of their farming systems and livelihoods. These could constitute remarkable attributes, considering the fact that farmers' knowledge and experience about place and context-specific strategies and approaches to reduce vulnerability or exposure (and/or increase adaptive capacity or resilience of their farming systems and livelihoods) represent crucial elements for an effective adaptation (Noble et al. 2014). Adaptive modifications in this study have been applied by all agroforesters, as a combination of agronomic, vegetative, structural and management practices, based on agroecological principles and focused on the improvement of key biophysical, socioeconomic and environmental components to support their sustainability and adaptation. It is important to note that the role of local institutions and individual/innovative farmers in the successful adoption of adaptation measures is reflected in most of agroforesters and conventional farmers' perceptions on the main training and inspiration sources for adopting adaptation measures (Table 7). Furthermore, the key role of indigenous/traditional might be more relevant in the case of the conventional farmers who do not have access to special training on adaptation measures (Table 7).

In the case of financial conditions to implement adaptation measures, and considering the high poverty and extreme poverty levels shown by Kayambi farmers, the availability of financial resources and support represents key factors to promote successful adaptation. In that sense, the similar economic input levels used by agroforesters and conventional farmers in implementing adaptation measures are not statistically significant to determine which type of farmer allocates greater financial resources on adaptation measures (Table 8). Despite that, conventional farmers in this study tend to allocate greater economic inputs in livestock management (considered in "Other cost" category in Table 8). Livestock management is mainly related to dairy farming, reported as the main livelihood cash income activity by these farmers (Study I). Lastly, the results of financial support provided by institutions to support adaptation (Table 9) differ from the well documented benefits derived from adaptation investment in agricultural sector (Chambwera et al. 2014), and from the well-known recognition of the role of public and private sectors to finance and support successful adaptation, at all levels (Chambwera et al. 2014, Noble et al. 2014). The almost non-existing financial support provided by public, private and civil society to implement adaptation measures in this study means that agroforesters and conventional farmers are coping and dealing alone with CCV and ECE. In that sense, the economic and financial adaptive capacity of Kayambi farmers could be categorised as low, due to the very low support provided by institutions and low levels of household income shown by Kayambi farmers (Table 6 and 8, respectively).

5.2. Some implications related to methods

The face-to-face interview method used in this study had both advantages and also disadvantages compared to other methods such as focus group discussions or key informant interviews, which could be used if village or community had been used as the comparison unit. Although face-to-face interviews could be seen as a time-consuming and high cost process when a large number of interviewers are needed, this method allows the collection of extensive data of all kinds within the same interview, showing also the highest response rate than other interview methods (Brenner et al. 1985, Neuman 1997).

In this study, where a long semi-structured and varied questionnaire was used, the face-to-face interview was the right method which allowed us to collect a large amount of data through an interactive and dynamic interview process. The costly attribute of face-to-face interview was avoided by the participation of only one interviewer (the author), while the time-consuming characteristic was unavoidable due to the long questionnaire. This, however, represented an important strategy to have a deep interaction with the interviewee and had positive influence in the data collection process. The face-to-face interview allows the researcher to invest the time needed for extensive explanations of the different sections of the questionnaires, assuring that the farmer had properly understood the context of the question, concepts and processes such as the meanings and types of soil, water and biological degradation, livelihood portfolios and their prioritisation, social environment conditions, supportive legal frameworks for adaptation, the types of recreation and cultural opportunities, adaptation measures, etc. In addition, due to the research being conducted in an indigenous cultural context, which is still characterised by an oral transmission of knowledge, including that of ecological and climate /weather predictions (Kovach 1964, Hosen et al. 2020, Williams and Riley 2020), face-to-face interviews with semi-structured questionnaires was a successful method to collect data.

Ethical issues related to indigenous people and traditional knowledge were carefully considered throughout the whole research process, included the pre-assessment to evaluate and select the study area as described in sections 1.4 and 3.1. The Confederation of the ITKP and the RESSAK supported the first field activities of this research by helping to identify the eligible AFS and CAS and making contact with the farmers. The Confederation of the ITKP also selected two local indigenous technicians/assistants to provide logistic and cultural support to the researcher during the interviews and field work46. In most of the cases the local assistant introduced the researcher to the farmer and was present during the interview. Because one of the local assistants was a woman, this aspect helped overcome sensitive gender aspects, especially in the case of indigenous peoples47, and facilitated the interactions between the researcher (a male) with the female farmers (the majority of interviewees) during the field work. The accompaniment of a woman as a local assistant/technician constituted crucial support to improve the participation of women.

Regarding the use of the photographs and data provided by farmers, the Kayambi leaders and farmers were informed about the details of the research and gave their permission to use and publish the data and photos for academic purposes. Anonymity of the participants was appropriately kept during whole research and publishing process. In addition, the acceptance and permits of local indigenous organisations represented unavoidable requirements to conduct an ethical and successful research in the ITKP.

[46] Local technicians were paid by the researcher with financial support received from VITRI.

[47] Where the socioeconomic roles of men and women are still based on traditional customs, with some restrictions on the participation of women, and usually conditioned to male dominated decisions.

Additionally, the main findings of this study will be shared with the Kayambi leaders and farmers in a culturally pertinent format in Spanish and possibly in Kichwa. In that regard, the findings of Study I have already been shared with the Kayambi leaders and farmers who participated in the research. This event was organised by the Confederation of the ITKP. A complementary socialisation event will be also organised to share the findings of Study II and Study III.

Moreover, a relevant aspect to be highlighted in relation to the methodological aspects in this study is the statistical data analysis of the WOCAT questionnaire on climate change. Although the analysis did not represent a new approach (it was conducted using basic tests, such as t-test, or chi-square), this study could be considered as one of the first attempts to statistically analyse, evaluate and visualise the data of WOCAT questionnaire on climate change. Compared with similar approaches, the WOCAT questionnaire on climate change represents a highly recommended option to evaluate the vulnerability to CCV of farming systems types or other SLM technologies48, as was previously mentioned in Section 2.2. On the other hand, the level of expertise needed to conduct the questionnaire, and the large number of parameters included in the evaluation, may restrict its popularisation and implementation as an approach to evaluate the vulnerability to CCV of farming systems in developing countries. To avoid the complexity and time consuming limitations of this approach, a simplified version of the questionnaire could be adapted to key parameters and processes, such as the main hazards and risks related to agrobiodiversity, soil fertility, water availability and use, and the socioeconomic features of livelihoods. Furthermore, applying the WOCAT questionnaire on climate change as a comparative research tool (as was done in this study) constitutes a dynamic, multidisciplinary, and challenging approach throughout the whole research process, especially for the collection, analysis, evaluation and visualisation of qualitative socioeconomic and biophysical data.

6. Conclusions and Recommendations

This study represents one of the first and most comprehensive studies to evaluate smallholder farmers' perceptions on the sustainability and vulnerability of farming systems in the ITKP, Ecuadorian Highlands, and potentially for the whole Tropical Andes. This research also provides comprehensive qualitative and quantitate evidence to demonstrate that AFS provide better biophysical and socioeconomic conditions than CAS to maintain and enhance sustainable farming systems and livelihoods. In addition, the multifunctional properties of AFS are a positive influence in reducing socioeconomic and environmental vulnerability of these farming systems and farmers' livelihoods to climate change, variability, and extreme events. The higher levels of agrobiodiversity reported in AFS suggest that AFS are more natural resource-based sustainable farming systems than CAS, which are less genetically diversified systems than AFS. Agroforesters reported better socioeconomic and environmental assets to sustain their livelihoods and households than conventional farmers, due to the higher agrobiodiversity found in their systems, especially in the case of the cultivated biodiversity. All of the socioeconomic parameters considered for the sustainability analysis suggest that AFS possess more advantages than CAS for supporting sustainable livelihoods and farming systems. More quantitative studies should, however, be carried out in order to complement some findings of this study (e.g. on-farm agrobiodiversity inventories in different crop seasons to evaluate more precisely the number of cultivated and wild species used by farmers). Regarding socioeconomic aspects such as agrobiodiversity usages, income levels and land tenure, it could be useful to have a better understanding of how the commercialisation of agrobiodiversity could improve farmers' income levels, and how improved income levels and better land tenure security could enhance sustainability through investments on productive assets for

[48] For example: terraces with improved seed and fertiliser application, riverbank stabilisation, minimum tillage, etc.

adaptation (e.g. infrastructure, equipment, technology and training). Moreover, it would also be interesting to know if the higher levels of agrobiodiversity reported in AFS could be related to better access to food and improvements in the nutritional conditions of smallholders' households, especially in children.

The methods and findings of this research suggest that the complete set of socioeconomic and environmental qualitative and quantitative data included especially in the WCCQV2 could represents an interesting and valid tool for the analysis of farming systems' vulnerability. In addition, the comparative analysis approach, the descriptive statistics (Crosstabs and Chi-square) and the inferential statistical test (Independent Samples t Test) applied for the analysis of the qualitative and quantitative data respectively, may represent one of the first scientific attempts to evaluate the WCCQV2. Furthermore, the qualitative data used in this study, based exclusively on farmer's perceptions, constitutes a good example of how indigenous/ traditional knowledge could be incorporated into the scientific approach. Taking into consideration the deficit of knowledge about traditional AFS and CAS in Tropical Highlands, the methods and findings of this study represent and alternative and interesting contribution and reference point to study socio-ecological systems. Due to the limited knowledge and geographical expansion of agroforestry practices along the study area and Ecuadorian highlands in general, this study could scientifically support current initiatives promoting trees and agroforestry as essential components to enhance sustainability, reduce vulnerability and increase resilience of farming systems and livelihoods of smallholder farmers. It is therefore highly recommended that AFS should be promoted and implemented as a priority socio-ecological approach for sustainable land management/change practices along the Ecuadorian Highlands, and potentially in other regions. Finally, more socioecological and multidisciplinary research will be needed in the High Andes in order to have a better understanding of the different characteristics and linkages among diverse farming approaches/practices and the strategies implemented by farmers to support sustainable and less vulnerable livelihoods in the global warming and change context.

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Annexes

Annex 1. Chronological development of socioeconomic and environmental/ecological indicators for sustainability and vulnerability in farming systems (adapted from Hayati 2017)

Reference	Main dimensions and indicators (farm level)		
	Economical	Social	Environmental / Ecological
Lockeretz 1988	Diversification of crops, on- and off- farm inputs	Agricultural practices to enhance farm's biological and economic stability: rotation; intercropping, relay cropping	Agrobiodiversity, nutrient recycling (compost, manure, nitrogen fixing legumes), soil permanent cover, livestock (low density), biological control of pest, weeds and diseases
Chambers 1991	Local non-farm income, formal employment, flexible credits	Migration and off-season opportunities, rights and access to productive assets (water, land, trees), and common property rights, included the security of those rights, transport, communication and information	Soil erosion, deforestation, salinisation
Dunlap et al. 1993	Improve farm economy/incomes, reduce reliance on purchased inputs, decrease complexity of food processing and distribution system	Improve health/well-being of rural residents, revitalise rural areas, ensure safe supply of wholesome food, increase the number of farms and farmers, improve site-specific knowledge of farmers	Increase diversity, protect and enhance soil, enhance environment and wildlife habitat, reduce agrichemical use, pattern agriculture after natural ecosystems, reduce energy use
Smith and McDonald 1997	Production cost, product prices, net farm income	Access to resources, skills, knowledge and planning capacity of farmers, awareness	Land capability, nutrient balance, biological activity, soil erosion, use of fertiliser/pesticide, water use efficiency
Scoones 1998	Economic or financial capital: capital base (cash, credit/debt, savings, and other economic assets, including basic infrastructure and production equipment and technologies)	Human and social capital: skills, knowledge, ability to labour, good health and physical capability, networks, social claims, social relations, affiliations, associations	Natural capital: natural resource stocks (soil, water, biodiversity, etc.) and environmental services (hydrological cycle, pollution sinks, etc.)
Hussein and Nelson 1998	Agricultural and non-agricultural activities diversification	Migration	

Reference	Main dimensions and indicators (farm level)		
	Economical	**Social**	**Environmental / Ecological**
Chen 2000	Total agricultural products, per capita food production, net farm income	Per-capita food supply, land tax, participation in decision-making	Use of external input, ground water quality, soil erosion, per-capita disaster loss, cropping index
Nambiar et al. 2001	Yield, income per labourer, real net output per unit land	Cultural level, number of varieties of livestock and organisms	Nutrient balance, efficiencies of fertilisers and irrigation/water uses, soil erosion, saline content and soil quality
Rasul and Thapa 2004	Land holding, crop area, labour; irrigation freq., quantity of ground wtaer, N, P, K, fertiliser used, productivity, farm income	Age and education level of respondent	Soil fertility status including soil pH, N, P,K and organic matter content
Sydorovych and Wossink 2008	Profit, income stability, reliance on purchased inputs and subsidies, sufficiency of cash flow, govt. regulation	Stress, risks, safety, nutrition, quality, taste, impact, animal care, attractiveness, odours, noise, info	Soil and water quality, agro and natural biodiversity, efficiency of natural resource use, solid waste disposal, air quality, GHG emissions
Pretty et al. 2008	Value chain, energy, water, local economy	Social and human capital, animal welfare	Soil fertility and health, soil loss, nutrients, pest management, biodiversity
Gomez-Limon and Riesgo 2008	Total gross margin, profit, public subsidies, gross domestic product contribution	Total labour, seasonal labour employment	Agro-diversity, soil cover, water use, nitrogen and energy balance, phosphorous risk
Guttenstein et al. 2010	Ratio of income/capita of farm, social integration and connectedness, diversity of farm, volume of goods and services	Nutritional status, extent of aboriginal participation, gender ratio, enrolment ratio in education, access and control to land, water and biodiversity	Ground and surface water consumption, biodiversity, % of land affected by desertification, carbon dioxide emissions
Gafsi and Favreau 2010	Viability, autonomy, transmissibility, efficiency	Working conditions, quality of life, local economy, social involvement	Agro-ecological: pollution control and soil fertility, crop rotation, agriculture and natural biodiversity, resources management
Vecchione 2010	Labour and land productivity, fragmentation, value addition,	Employment in agriculture, old-age index, education, gender composition, population	Arable surfaces, permanent crops, poplar wood, woods, other surfaces, biodiversity

Reference	Main dimensions and indicators (farm level)		
	Economical	Social	Environmental / Ecological
	diversification, mechanisation		
Hayati et al. 2011	Crop productivity, net farm income, cost/benefit ratio of production, per-capita food grain production	Food self-sufficiency, equality in income and food distribution, access to resources and support services, farmers' knowledge and awareness of resource conservation	Amounts of fertiliser, pesticide and water used, soil nutrient content, ground water table, water use efficiency, quality of ground water and nitrate content of ground water and crops
OECD 2013, OECD 2014	Agricultural GDP and outputs, agricultural production volume, farm employment, number of farms, farm income, agri-environmental expenditure	Farmer age/gender distribution, farmer education, agricultural support, structure and management of landscapes	Soil erosion, water resources, quality and use, greenhouse gases, ammonia and methyl bromide, agro and natural biodiversity, wildlife habitats, nutrient, pesticides and energy uses, agricultural land cover, land use types
Hrebícek et al. 2013	Farm income, net margin, indebtedness, gross margin, liquidity, profitability	Salary, working hours, holidays, education and training, safety and health protection at work, workers participation, social engagement	Balances of NO, P and K, organic matter balance, specific energy consumption, intensity of plant protection, soil erosion, system diversity potential
Van Pham and Smith 2014	Crop productivity, net farm income	Food self-sufficiency, access to services and resources	Soil fertility, pest and disease occurrence, W use efficiency, use of chemical fertiliser, use of chemical pesticide
Waney et al. 2014	Productivity, cost of production, farm income, product quality, product price stability, marketing network, producer/buyer relationship	Local community engagement, resources availability/accessibility, support system accessibility, knowledge about resource conservation, stakeholder support	Land preparation, erosion control, nutrient and soil fertility management, use of fertiliser, intensity of land occupation, cropping system, weed control, pest and disease control
Pandey et al. 2016	Sensitivity: Farm output, crop residue, grass and Tree product (fodder and fuelwood)	Adaptive capacity: Food insufficiency, literacy	Exposure: Temperature and precipitation variation. Sensitivity: water availability, soil fertility and loss. Adaptive capacity: Tree planted, fertiliser and manure application
Latruffe et al. 2016	Economic viability is mainly measured through profitability,	Wellbeing, physical health, quality of life, social diversification, image of	Nutrients, pesticides, non-renewable resources (i.e. energy and water), land

Reference	Main dimensions and indicators (farm level)		
	Economical	Social	Environmental / Ecological
	liquidity, stability, productivity and autonomy	farmers/agriculture in communities	management, emissions of GHG and acidifying substances, biodiversity, and physical, chemical and biological soil quality
Hayati 2017	Net farm income, profitability, labour, markets and commercialisation, government regulations, incentives and subsidies, crop production and yield, mechanisation	Access to resources (water, land, credit, technology, information), human capital (farmer's skills, education, awareness, health), nutrition and food security/self-sufficiency, gender composition, participation of indigenous people and elders, local community and social engagement, social environment and networks (security , farmers' cooperatives, associations and unions), employment in agriculture	Soil erosion and fertility, soil organic matter, physical, chemical and biological soil quality, ground and surface water quality, irrigation sources and water use efficiency use and types of fertilisers and pesticides, agro and natural biodiversity, nutrient balance, pollution of soil and water, greenhouse gases emissions, trees and woods, management practices, cropping system and type of farming
Leakey 2017	Income, marketing, trade	Health, gender equality, tradition and culture	Soils, climate, biodiversity
Genari and Navarro 2019	Farm output value per hectare, net farm income, risk mitigation mechanisms	Wage rate in agriculture, food insecurity experience scale (FIES), secure tenure rights to land	Prevalence of soil degradation, variation in water availability, management of fertilisers, management of pesticides, use of biodiversity-supportive practices

Annex 2. SAFA sustainability dimensions, themes, sub-themes and indicators (FAO 2013)

Sustainability Dimension G: GOOD GOVERNANCE		
Themes	Sub-Themes	Default Indicators
G1 Corporate Ethics	G1.1 Mission Statement	G 1.1.1 Mission Explicitness
		G 1.1.2 Mission Driven
	G 1.2 Due Diligence	G 1.2.1 Due Diligence
G2 Accountability	G 2.1 Holistic Audits	G 2.1.1 Holistic Audits
	G 2.2 Responsibility	G 2.2.1 Responsibility
	G 2.3 Transparency	G 2.3.1 Transparency
G3 Participation	G 3.1 Stakeholder Dialogue	G 3.1.1 Stakeholder Identification
		G 3.1.2 Stakeholder Engagement
		G 3.1.3 Engagement Barriers
		G 3.1.4 Effective Participation
	G 3.2 Grievance Procedures	G 3.2.1 Grievance Procedures
	G 3.3 Conflict Resolution	G 3.3.1 Conflict Resolution
G4 Rule of Law	G 4.1 Legitimacy	G 4.1.1 Legitimacy
	G 4.2 Remedy, Restoration and Prevention	G 4.2.1 Remedy, Restoration and Prevention
	G 4.3 Civic Responsibility	G 4.3.1 Civic Responsibility
	G 4.4 Resource Appropriation	G 4.4.1 Free, Prior and Informed Consent
		G 4.4.2 Tenure rights
G5 Holistic Management	G 5.1 Sustainability Management Plan	G 5.1.1 Sustainability Management Plan
	G 5.2 Full-Cost Accounting	G 5.2.1 Full-Cost Accounting

Sustainability Dimension E: ENVIRONMENTAL INTEGRITY		
Themes	Sub-Themes	Default Indicators
E1 Atmosphere	E 1.1 Greenhouse Gases	E 1.1.1 GHG Reduction Target
		E 1.1.2 GHG Mitigation Practices
		E 1.1.3 GHG Balance
	E 1.2 Air Quality	E 1.2.1 Air Pollution Reduction Target
		E 1.2.2 Air Pollution Prevention Practices
		E 1.2.3 Ambient Concentration of Air Pollutants
E2 Water	E 2.1 Water Withdrawal	E 2.1.1 Water Conservation Target
		E 2.1.2 Water Conservation Practices
		E 2.1.3 Ground and Surface Water Withdrawals
	E. 2.2 Water Quality	E 2.2.1 Clean Water Target
		E 2.2.2 Water Pollution Prevention Practices
		E 2.2.3 Concentration of Water Pollutants
		E 2.2.4 Wastewater Quality
E3 Land	E 3.1 Soil Quality	E 3.1.1 Soil Improvement Practices
		E 3.1.2 Soil Physical Structure
		E 3.1.3 Soil Chemical Quality
		E 3.1.4 Soil Biological Quality
		E 3.1.5 Soil Organic Matter
	E 3.2 Land Degradation	E 3.2.1 Land Conservation and Rehabilitation Plan
		E 3.2.2 Land Conservation and Rehabilitation Practices
		E 3.2.3 Net Loss/Gain of Productive Land
E4 Biodiversity	E 4. 1 Ecosystem Diversity	E 4.1.1 Landscape/Marine Habitat Conservation Plan
		E 4.1.2 Ecosystem Enhancing Practices
		E 4.1.3 Structural Diversity of Ecosystems
		E 4.1.4 Ecosystem Connectivity
		E 4.1.5 Land Use and Land Cover Change

Sustainability Dimension E: ENVIRONMENTAL INTEGRITY		
Themes	Sub-Themes	Default Indicators
E4 Biodiversity	E 4.2 Species Diversity	E 4.2.1 Species Conservation Target
		E 4.2.2 Species Conservation Practices
		E 4.2.3 Diversity and Abundance of Key Species
		E 4.2.4 Diversity of Production
	E. 4.3 Genetic Diversity	E 4.3.1 Wild Genetic Diversity Enhancing Practices
		E 4.3.2 Agro-biodiversity in-situ Conservation
		E 4.3.3 Locally Adapted Varieties and Breeds
		E 4.3.4 Genetic Diversity in Wild Species
		E 4.3.5 Saving of Seeds and Breeds
E5 Materials and Energy	E 5.1 Material Use	E 5.1.1 Material Consumption Practices
		E 5.1.2 Nutrient Balance
		E 5.1.3 Renewable and Recycled Materials
		E 5.1.4 Intensity of Material Use
	E 5.2 Energy Use	E 5.2.1 Renewable Energy Use Target
		E 5.2.2 Energy Saving Practices
		E 5.2.3 Energy Consumption
		E 5.2.4 Renewable Energy
	E 5.3 Waste Reduction and Disposal	E 5.3.1 Waste Reduction Target
		E 5.3.2 Waste Reduction Practices
		E 5.3.3 Waste Disposal
		E 5.3.4 Food Loss and Waste Reduction
E6 Animal Welfare	E 6.1 Animal Health	E 6.1.1 Animal Health Practices
		E 6.1.2 Animal Health
	E 6.2 Freedom from Stress	E 6.2.1 Humane Animal Handling Practices
		E 6.2.2 Appropriate Animal Husbandry
		E 6.2.3 Freedom from Stress

Sustainability Dimension C: ECONOMIC RESILIENCE		
Themes	Sub-Themes	Default Indicators
C1 Investment	C 1.1 Internal Investment	C 1.1.1 Internal Investment
	C 1.2 Community Investment	C 1.2.1 Community Investment
	C 1.3 Long Ranging Investment	C 1.3.1 Long Term Profitability
		C 1.3.2 Business Plan
	C 1.4 Profitability	C 1.4.1 Net Income
		C 1.4.2 Cost of Production
		C 1.4.3 Price Determination
C2 Vulnerability	C 2.1 Stability of Production	C 2.1.1 Guarantee of Production Levels
		C 2.1.2 Product Diversification
	C 2.2 Stability of Supply	C 2.2.1 Procurement Channels
		C 2.2.2 Stability of Supplier Relationships
		C 2.2.3 Dependence on the Leading supplier
	C 2.3 Stability of Market	C 2.3.1 Stability of Market
	C 2.4 Liquidity	C 2.4.1 Net Cash Flow
		C 2.4.2 Safety Nets
	C 2.5 Risk Management	C 2.5.1 Risk Management
C3 Product Quality and Information	C 3.1 Food Safety	C 3.1.1 Control Measures
		C 3.1.2 Hazardous Pesticides
		C 3.1.3 Food Contamination
	C 3.2 Food Quality	C 3.2.1 Food Quality
	C 3.3 Product Information	C 3.3.1 Product Labelling
		C 3.3.2 Traceability System
		C 3.3.3 Certified Production
C4 Local Economy	C 4.1 Value Creation	C 4.1.1 Regional Workforce
		C 4.1.2 Fiscal Commitment
	C 4.2 Local Procurement	C 4.2.1 Local Procurement

Sustainability Dimension S: SOCIAL WELL-BEING		
Themes	Sub-Themes	Default Indicators
S1 Decent Livelihood	S 1.1 Quality of Life	S 1.1.1 Right to Quality of Life
		S 1.1.2 Wage Level
	S 1.2 Capacity Development	S 1.2.1 Capacity Development
	S 1.3 Fair Access to Means of Production	S 1.3.1 Fair Access to Means of Production
S2 Fair Trading Practices	S 2.1 Responsible Buyers	S 2.1.1 Fair Pricing and Transparent Contracts
	S 2.2 Rights of Suppliers	S 2.2.1 Rights of Suppliers
S3 Labour Rights	S 3.1 Employment Relations	S 3.1.1 Employment Relations
	S 3.2 Forced Labour	S 3.2.1 Forced Labour
	S 3.3 Child Labour	S 3.3.1 Child Labour
	S 3.4 Freedom of Association and Right to Bargaining	S 3.4.1 Freedom of Association and Right to Bargaining
S4 Equity	S 4.1 Non Discrimination	S 4.1.1 Non Discrimination
	S 4.2 Gender Equality	S 4.2.1 Gender Equality
	S 4.3 Support to Vulnerable People	S 4.3.1 Support to Vulnerable People
S5 Human Safety and Health	S 5.1 Workplace Safety and Health Provisions	S 5.1.1 Safety and Health Trainings
		S 5.1.2 Safety of Workplace, Operations and Facilities
		S 5.1.3 Health Coverage and Access to Medical care
	S 5.2 Public Health	S 5.2.1 Public Health
S6 Cultural Diversity	S 6.1 Indigenous Knowledge	S 6.1.1 Indigenous Knowledge
	S 6.2 Food Sovereignty	S 6.2.1 Food Sovereignty

Annex 3. Questionnaire used in Study I

1. General Information

Interview No: Date:

Farmer name:

Province: Canton: Community:

Altitude (m.a.s.l): Coordinates: Slope (%):

2. Main Agroecosystem aspects:

Agroecosystem type	*Agroforestry*	
	Conventional	

Main land use	Area (ha)	Age (years):	Remarks
Crops and trees/shrubs			
Pastures and trees/shrubs			
Only crops: *(monocrops/many crops/rotative crops)*			
Only pastures: *(planted pastures, meadows)*			
Others, specify: *(grazing communal area, own or communal native forest remnants)*			
Total			

3. Main socioeconomic aspects:

Ethnic group	*Indigenous*		Nationality/ People:
	Mestizo		

Main livelihoods description:

Main cash income livelihoods :

Income categorisation:

	Low (< 375 USD)	Moderate (= 375 USD)	High (> 375 USD)
On-farm income			
Off-farm income at household level			

Irrigation sources				Remarks
Irrigation system		Type		
Rainfed only		Period/months		
Reservoir		Capacity (m3)		
Other/specify:				

Land tenure		Remarks
Formal owner		
Informal owner		
Other/specify:		

4. Agrobiodiversity

Cultivated biodiversity				
Forestry component Trees and shrubs (included fruit species):				
Species	Cultivars/Breeds	Subsistence Use	Commercial Use	Mixed Used Subst/Comm %
Crops component Grains and legumes:				
Tubers and roots:				
Fruits (other fruits different from trees and shrubs:				
Vegetables:				
Pastures (included wild species in meadows):				
Medicinal, aromatic and condiment species (planted):				

4. Agrobiodiversity (continuation)

Animal component Livestock :				
Species	Cultivars/Breeds	Subsistence Use	Commercial Use	Mixed Use Subst/Comm %
Minor animals:				
Other species/varieties component (ornamental, cultural, burden species, etc.)				
Associated biodiversity				
Wild plants:				
Wild animals:				
Birds				
Reptiles				
Amphibians				
Mammals				
Invertebrates				

Annex 4. Questionnaire used in studies II and III (adapted from WOCAT climate change questionnaire version 2).

Exposure: General observations of climate change / climatic variability

		Observed by farmer in the last 10 years			**Expectation by the farmer for the future**		
		Decr.(-)	**Stable**	**Incr.(+)**	**Decr.(-)**	**Stable**	**Incr.(+)**
1.1. Gradual climate changes							
1.1.1 Temperature	Annual temperature						
	Wet / rainy season						
	Dry season						
1.1.2 Precipitation	Annual rainfall						
	Wet / rainy season						
	Dry season						
1.2. Extreme events							
Heavy* rainfall events							
Heavy hail events							
Heavy windstorms							
Droughts / dry periods							
Heat waves / warm periods							
Cold periods/frost							
1.3. Other climatic and climate-related stressors							
Glacier retrieve							
Floods							
Fires							
Pest, weeds and disease outbreaks							

2. Sensitivity of the main farming system's biophysical components : Control of impacts

2.1 Indicate and prioritise the main gradual climate change / extreme climate events affecting the farming system ♦:		
How does the farming system help controlling impacts of extreme climate events and gradual climate changes?	**Ranking ◊**	**Comments/specify**
2.2 Controlling soil erosion by water		
Control of raindrop splash (splash erosion)		
Control of dispersed runoff: (sheet or interrill erosion)		
Control of concentrated runoff: (Rill and gully erosion)		
Reduction of slope angle		
Reduction of slope length		
Sediment retention / trapping, sediment harvesting		
2.3 Controlling soil erosion by wind		
Reduction in wind speed		
2.4 Controlling chemical soil deterioration		
Increase in organic matter		
Increase in nutrient availability (supply, recycling,…)		

Reduction of salinity		
2.5 Controlling physical soil deterioration		
Increase of surface roughness		
Improvement of surface structure (crusting, sealing)		
Improvement of topsoil structure (compaction)		
Improvement of subsoil structure (hardpan)		
Stabilisation of soil (e.g. by tree roots against landslides)		
Increase of infiltration		
2.6 Controlling biological degradation		
Improvement of ground cover		
Increase of biomass (quantity)		
Promotion of suitable vegetation species and varieties (quality, e.g. palatable fodder)		
Promotion of suitable crop varieties		
Increase in crop diversification		
Increase in pest control		
Increase of beneficial species		
Reduction of invasive alien species		
Control of fires		
Reduction of dry material (fuel for wildfires)		
Promotion of suitable livestock varieties		
Increase in livestock diversification		
Spatial arrangement and diversification of land use		
2.7 Controlling Water degradation		
Increase / maintain water stored in soil		
Improvement of harvesting / collection of water (runoff, dew, snow, etc.)		
Reduction of evaporation		
Increase of groundwater level, recharge of groundwater		
Water spreading		
Improvement of water quality, buffering/filtering water		
2.8 Others (specify)		

♦ example: increase or decrease on temperature, rains, droughts, winds, radiation, cold periods/frost, winds, pests, etc.;
◊ 3 = very important / large extent ; 2 = important / medium extent; 1 = less important / little extent

3. Gradual climate change / extreme climate events impacts and causes

3.1 Grading the impacts of gradual climate changes and extreme climate events			
Indicate the impacts (benefits / disadvantages) of gradual climate changes and extreme climate events	**Impacts**		
	Decreased / deteriorated	**No impact**	**Increased / Improved**
3.1.1 On-site impacts			
3.1.1.1 Socio-economic impacts			
Crop yield			
Fodder production			

Fodder quality			
Animal production			
Wood production			
Risk of production failure			
Drinking / household water availability / quality			
Irrigation water availability / quality			
Demand for irrigation water			
Expenses on agricultural inputs			
Farm income			
Diversification of income sources			
Production area (new land under cultivation / use)			
Labour constraints			
Workload			
Difficulty of farm operations			
Product diversification			
3.1.1.2 Socio-cultural impacts			
Cultural opportunities(e.g. spiritual, aesthetic, others)			
Recreational opportunities			
Community institution strengthening			
Conservation / erosion knowledge			
Conflicts			
Position of socially and economically disadvantaged groups (gender, age, status, ethnicity, etc.)			
Food security / self-sufficiency (dependence on external support)			
Health			
3.1.1.3 Ecological impacts			
Water quantity			
Water quality			
Harvesting / collection of water			
Soil moisture			
Evaporation			
Surface runoff			
Excess water drainage			
Recharge of groundwater table / aquifer			
Wind velocity			
Soil cover			
Biomass / above ground C			
Nutrient cycling / recharge			
Soil organic matter / below ground C			
Emission of carbon and greenhouse gases			
Soil loss			
Soil crusting / sealing			
Soil compaction			
Salinity			
Fire risk			
Animal diversity			

Plant diversity			
Invasive alien species			
Beneficial species (predators, earthworms, pollinators)			
Biological pests / diseases			
Habitat diversity			
3.1.2 Off-site impacts			
Water availability (groundwater, springs)			
Downstream flooding			
Stream flow in dry season / reliable and stable low flows			
Sediment yield			
Downstream siltation			
Groundwater / river pollution			
Buffering / filtering capacity (by soil, vegetation, wetlands)			
Wind transported sediments			
Damage on neighbours' field			
Damage on public / private infrastructure			

4. Adaptive capacity of the farmer

Main socioeconomic assets for adaptation	Low	Moderate	High
4.1 Economic opportunities			
Financial resources from:			
On-farm income			
Off-farm income ♦ at household level			
Remittance income at household level			
Loan options			
Access to market			
4.2 Social environment			
Connection to social networks (e.g. associations, village organisations)			
Stability of social environment			
Legal framework supportive of adaptation			
Policies in place supportive of adaptation			
Clear institutional responsibilities for climate change related tasks			
4.3 Information access			
Access to reliable weather forecast information			
Access to early warning systems related to climate hazards / shocks			
Access to education and training related to climate change (extension / advisory service)			
Knowledge on adequate and timely adaptation in land management related to climate hazards / shocks			
Good communication / information sharing between land users / other stakeholders (policy makers, researchers) related to climate variability (feedback mechanism)			
4.4 Other resources			
Level of infrastructure			
Availability of construction material and equipment			
Availability of energy supplies			

♦ Off-farm income: income other than from the use of cropland, grazing land, forest and mixed land (e.g. business, trade, manufacturing, industry).

5. Adaptation experiences

5.1 Was the production system adapted / modified to become more tolerant (last 10 years)? No ☐ Yes ☐
5.1.2 (If yes) Specification of adaptation measure Specify which measures were modified or newly added (Several answers possible) Agronomic measures ♦ ☐ Vegetative measures ♣ ☐ Structural measures ◊ ☐ Management measures † ☐
5.1.3 Give details of adaptations / modifications (design, material/species)
Comments:
5.1.4 By whom / by what did land user(s) get inspired to do the adaptation measure(s) by land users* alone (self-initiative / bottom-up) ☐ mainly by land users supported by SLM specialists/agricultural advisor ☐ by other land users ☐ mainly by input from SLM specialists/agricultural advisor ☐ by SLM specialists/agricultural advisor alone (top-down) ☐ by researchers ☐ other (specify): ☐
5.2 Did the land user(s) get any technical training on adaptation measures? No ☐ Yes ☐
5.2.1 If yes, by whom?
5.2.2 If no, from where did they get the knowledge?

♦ such as conservation agriculture, manuring/composting, mixed cropping, contour cultivation, mulching, etc.; ♣ tree planting, hedge barriers, grass strips, windbreaks, agroforestry, etc.; ◊ terraces, banks, bunds, constructions, palisades, etc.; † land use change, area closure, rotational grazing

6. Annual inputs for adaptation / List of inputs and materials used for adaptation

	Specify inputs	Quantity (person days, kg, l, etc.)	Total cost in US$ per unit (ha, m3 etc.)
6.1 Labour	Family labour		
	Haired labour		
6.2 Equipment	Machine hours		
	Animal traction		
	Tools		
	Others (specify):		
6.3 Construction material	Stone Wood Earth		
	Wood		
	Earth		
	Others (specify):		
6.4 Agricultural	Seeds		
	Seedlings		
	Fertilisers		
	Biocides		
	Compost/Humus/Manure		
	Others (specify):		
6.5 Others specify):			

7. Financial support / Did the land user(s) get any financial support for adaptation measures?

What percentages of Approach costs were met by the following contributors / donors?

	Specify:	%
International		
Central government		
International non-government		
National non-government		
Private sector		
Local government or community		
Local community / farmer(s)		
Others:		

Annex 5. Agrobiodiversity differences between AFS and CAS (modified based on Table 1 in Study I (Córdova et al. 2018))

Agrobiodiversity	# of spp.		% of Difference [a]		# of Cultivars/Breeds		% of Difference [a]	
	AFS°	CAS°			AFS°	CAS°		
Cultivated Biodiversity (Subtotal 1)								
Trees and shrubs	32	13	44	****	33	13	44	****
Legumes and grains	9	8	11	***	21	13	24	***
Tubers and roots	5	4	12	**	11	7	19	**
Non-tree and shrub fruits	3	2	25	****	3	2	26	****
Vegetables	21	11	31	****	25	12	34	****
Pastures	8	6	12	**	8	6	12	**
Medicinal, aromatic and condiment plants	11	4	44	****	11	4	45	****
Livestock †	1	1	3		1	1	3	
Minor animals ‡	4	3	22	****	4	3	23	****
Other (draught animals, ornamental and cultural spp.)	7	3	39	***	-	-	-	
Subtotal 1	102	54	30	****	118	62	31	****
Associated Biodiversity (Subtotal 2)								
Wild animals:								
Birds	13	11	8	**	-	-	-	
Reptiles	2	2	6		-	-	-	
Amphibians	2	2	14	**	-	-	-	
Mammals	5	4	8	**	-	-	-	
Invertebrates	30	27	5		-	-	-	
Wild animals (Subtotal 2.1)	52	46	6	**	-	-	-	
Wild plants (Subtotal 2.2)	18	13	15	****	-	-	-	
Subtotal 2 (Subtotal 2.1 + Subtotal 2.2)	70	59	8	***	-	-	-	
Total (Subtotal 1 + Subtotal 2)	172	113	20	****	118	62	31.2	****

° n = 30; * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$; **** $p < 0.001$; - Not applicable; [a] = [(AFS spp. – CAS spp.) (100)] / (AFS spp. + CAS spp.); † ruminants and pseudo ruminants: cows, sheep, goats, llamas and alpacas; ‡ guinea pigs, rabbits, pigs, chickens, turkeys, ducks, quails and geese

Annex 6. Soil parameters differences between AFS and CAS (modified based on Table A3 in Study I (Córdova et al. 2018))

Soil Samples	pH		EC **		SOM ◊		N		P		K		CEC ©		Texture	BD ¤	FC º	MY †	MAB ‡
			dS/cm		%		%		ppm		meq/100g		meq/100g		Class	(g/cc)	(%)	(CFU/g)	(CFU/g)
Agroforestry Systems																			
1	6.2	L	0.3	L	5.4	O	0.3	O	39.2	O	1.2	O	18.4	O	Sandy loam	1.2	35.6	127,000	1,273,000
2	7.2	H	0.3	L	4.1	O	0.2	O	44.5	O	1.2	O	19.6	O	Sandy loam	1.4	47.9	54,000	1,640,000
3	6.3	L	0.3	L	4.8	O	0.2	O	48.8	O	0.7	O	16.6	O	Sandy loam	1.3	23.6	104,000	818,000
4	7.1	H	0.3	L	3.6	O	0.2	O	57.3	O	1.2	O	18.4	O	Sandy loam	1.4	34.8	27,000	1,820,000
5	7.7	H	0.7	O	4.2	O	0.2	O	40.6	O	2.8	H	20.9	O	Sandy loam	1.3	40.0	54,000	5,364,000
6	6.5	O	0.1	L	3.2	O	0.2	O	31.9	O	0.7	O	19.2	O	Sandy loam	1.6	10.0	86,000	5,864,000
7	6.2	L	0.1	L	3.5	O	0.2	O	29.3	O	0.3	O	16.4	O	Sandy loam	1.3	16.1	180,000	3,864,000
8	6.1	L	0.2	L	3.4	O	0.2	O	33.6	O	0.6	O	19.7	O	Sandy loam	1.4	20.3	209,000	5,818,000
Mean	6.6	O	0.3	L	4.0	O	0.2	O	40.6	O	1.1	O	18.6	O	-	1.4	28.5	105,125	3,307,625
Conventional Agriculture Systems																			
1	6.2	L	0.2	L	5.1	O	0.3	O	53.1	O	1.3	O	18.9	O	Sandy loam	1.4	28.3	59,000	182,000
2	7.4	H	0.4	L	3.0	L	0.1	L	31.3	O	0.9	O	16.7	O	Sandy loam	1.5	32.9	82,000	1,540,000
3	6.4	L	0.4	L	3.5	O	0.2	O	23.6	O	1.2	O	17.9	O	Sandy loam	1.6	31.2	127,000	3,360,000
4	6.7	O	0.2	L	3.1	L	0.2	O	17.1	O	0.7	O	15.3	O	Sandy loam	1.1	26.3	182,000	2,727,000
5	6.6	O	0.4	L	3.1	L	0.2	O	27.9	O	0.6	O	22.4	O	Sandy loam	1.5	22.8	109,000	5,636,000
6	7.1	H	0.1	L	2.4	L	0.1	L	0.0	L	0.4	O	21.8	O	Sandy loam	1.6	38.5	36,000	4,545,000
7	5.9	L	0.2	L	3.1	O	0.2	O	14.8	L	0.5	O	14.6	O	Sandy loam	1.5	40.1	145,000	7,318,200
8	5.8	L	0.2	L	4.0	O	0.2	O	14.9	L	0.3	O	11.4	O	Sandy loam	1.0	30.5	104,000	5,681,800
Mean	6.5	O	0.3	L	3.4	O	0.2	O	22.8	O	0.7	O	17.4	O	-	1.4	31.3	105,500	3,873,750
t Sig.*	0.590		0.566		0.137		0.137		0.015		0.272		0.387		-	0.683	0.591	0.990	0.625

*α = 0.05; ** Soil Electrical Conductivity; ◊ Soil Organic Matter; © Cation Exchange Capacity; ¤ Bulk density; º Field capacity;† Moulds and yeast; ‡ Mesophilic aerobic bacteria; - Not apply.

Analysis methods: pH: 1:1.25 H2O; SOM:0.1-0.5 K2Cr2O7 0.8 N; P & K : Modified Olsen ; CEC: Ammonium Acetate 1N pH 7.0; CE: Saturated Paste; BD and FC: Physical methods; Moulds and yeast/Mesophilic aerobic bacteria: AOAC 990.12 (Petrifilm).

Evaluation: H = High; O = Optimal; L = Low. Evaluated and analysed by the water and soil laboratory of the Salesian Polytechnic University, Cayambe-Ecuador.

Annex 7. Microclimate conditions inside AFS and CAS (modified based on Table A4 in Study I (Córdova et al. 2018))

Inside farm records	Temp (C°)	Temp high (C°)	Temp low (C°)	Humidity (%)	Dew point (C°)	Wind speed (m/s)	Wind high speed (m/s)	Wind chill (C°)	Heat index (C°)
Agroforestry systems									
1	16.1	16.4	15.7	78.2	11.9	2.3	5.2	15.6	16.0
2	14.8	15.0	14.6	85.2	11.9	1.3	3.0	14.7	14.9
3	15.4	15.7	15.2	94.3	14.4	0.3	1.5	15.4	15.8
4	17.0	17.5	16.6	82.6	13.7	1.0	3.2	17.0	17.3
5	18.2	18.6	17.8	80.2	14.4	0.9	3.8	18.2	18.5
6	16.3	16.6	16.1	95.4	15.5	1.3	3.1	16.3	16.7
7	17.7	18.0	17.3	88.9	15.6	1.0	2.7	17.7	18.1
8	16.7	17.1	16.4	90.6	15.0	0.8	2.7	16.7	17.1
Mean	16.5	16.9	16.2	86.9	14.1	1.1	3.1	16.5	16.8
Conventional agricultural systems									
1	15.9	16.2	15.6	91.8	14.5	1.1	3.0	15.9	16.2
2	16.5	16.7	16.2	94.2	15.4	0.3	1.6	16.5	16.9
3	16.4	16.8	16.0	80.2	12.7	2.1	4.7	16.1	16.5
4	16.2	16.6	15.8	83.0	13.0	1.0	3.1	16.2	16.4
5	17.2	17.6	16.8	79.6	13.4	2.6	6.4	16.9	17.3
6	15.2	15.5	14.9	87.6	12.9	2.0	3.8	14.9	15.3
7	15.2	15.6	14.9	92.6	13.9	1.0	2.7	15.2	15.6
8	16.8	17.1	16.5	86.8	14.5	2.2	6.1	16.6	17.1
Mean	16.2	16.5	15.8	87.0	13.8	1.5	3.9	16.0	16.4
t Sig. *	0.437	0.483	0.407	0.989	0.670	0.238	0.281	0.394	0.430

*α = 0.05

Annex 8. Differences on agrobiodiversity uses between AFS and CAS (modified based on Table 2 in Study I (Córdova et al. 2018))

Agrobiodiversity	# of Subsistence/Functional spp.		% of Difference [a]		# of Commercial spp.		% of Difference [a]	
	AFS°	CAS°			AFS°	CAS°		
Cultivated biodiversity (Subtotal 1)								
Trees and shrubs	31	12	43	****	1	0	89	*
Legumes and grains	7	7	1		2	1	41	**
Tubers and roots	4	3	9		1	0	40	*
Non-tree and shrub fruits	3	2	23	***	0	0	52	**
Vegetables	12	9	16	**	8	2	59	****
Pastures	8	6	10	**	0.3	0	100	
Medicinal, aromatic and condiment plants	8	4	34	****	3	0.1	91	**
Livestock †	1	0	15		1	1	7	
Minor animals ‡	3	2	18	***	1	0.5	38	**
Other (draught animals, ornamental and cultural spp.)	7	3	39	***	0.2	0	100	
Subtotal 1	84	49	26	****	17	5	56	****
Associated biodiversity (Subtotal 2)								
Wild animals:								
Birds	13	11	8	**	0	0	0	
Reptiles	2	2	6		0	0	0	
Amphibians	2	2	14	**	0	0	0	
Mammals	5	4	8	**	0	0	0	
Invertebrates	30	27	5		0	0.03	100	
Wild animals (Subtotal 2.1)	52	46	6	**	0	0.03	100	
Wild plants (Subtotal 2.2)	18	13	15	****	0	0.03	100	
Subtotal 2 (Subtotal 2.1 + Subtotal 2.2)	70	59	8	***	0	0.1	100	
Total (Subtotal 1 + Subtotal 2)	154	108	17	****	17	5	56	****

° n = 30; * $p < 0.1$; ** $p < 0.05$; ** $p < 0.01$; **** $p < 0.001$; - Not applicable; [a] = [(AFS spp. – CAS spp.) (100)] / (AFS spp. + CAS spp.); † ruminants and pseudo ruminants: cows, sheep, goats, llamas and alpacas; ‡ guinea pigs, rabbits, pigs, chickens, turkeys, ducks, quails and geese.

Annex 9. Differences of biophysical controlling factors levels to the impacts of main gradual climate changes, extremes and other climate-related events between AFS and CAS (modified based on Table 3 in Study II (Córdova et al. 2019)).

Biophysical Controlling Factors	**Controlling Level Perceptions (%)**						**Pearson Chi-Square**	
	AFS ᵠ			**CAS ᵠ**			**Asymp. Sig.**	**Significance**
	1	**2**	**3**	**1**	**2**	**3**	**(2-sided)**	
Controlling soil erosion by water †	**2**	**16**	**82**	**68**	**25**	**7**	**0.000**	****
Control of raindrop splash (splash erosion)	0	10	90	53	40	7	0.000	****
Control of dispersed runoff (sheet or interrill erosion)	0	13	87	53	40	7	0.000	****
Control of concentrated runoff (rill and gully erosion)	0	10	90	53	40	7	0.000	****
Reduction of slope angle	7	20	73	83	10	7	0.000	****
Reduction of slope length	7	27	67	90	3	7	0.000	****
Sediment retention/trapping, sediment harvesting	0	17	83	73	17	10	0.000	****
Controlling soil erosion by wind /reduction in wind speed	**0**	**17**	**83**	**60**	**23**	**17**	**0.000**	****
Controlling chemical soil deterioration †	**12**	**10**	**78**	**51**	**32**	**17**	**0.000**	****
Increase in organic matter	0	7	93	13	57	30	0.000	****
Increase in nutrient availability (supply, recycling…)	0	13	87	60	27	13	0.000	****
Reduction of salinity	37	10	53	80	13	7	0.000	****
Controlling physical soil deterioration †	6	17	77	48	38	13	0.000	****
Increase of surface roughness	3	13	83	30	63	7	0.000	****
Improvement of surface structure (crusting, sealing)	3	13	83	43	37	20	0.000	****
Improvement of topsoil structure (compaction)	3	23	73	63	27	10	0.000	****
Improvement of subsoil structure (hardpan)	7	33	60	53	37	10	0.000	****
Stabilisation of soil (e.g., by tree roots against landslides)	10	10	80	67	27	7	0.000	****
Increase of infiltration	7	10	83	33	40	27	0.000	****
Controlling biological degradation †	**4**	**8**	**88**	**39**	**36**	**25**	**0.000**	****
Improvement of ground cover	0	3	97	23	43	33	0.000	****
Increase of biomass (quantity)	0	0	100	20	53	27	0.000	****
Promotion of suitable vegetation species and varieties (quality, e.g., palatable fodder)	0	3	97	33	33	33	0.000	****
Promotion of suitable crop varieties	0	0	100	40	30	30	0.000	****
Increase in crop diversification	0	3	97	37	37	27	0.000	****
Increase in pest control	3	17	80	60	30	10	0.000	****
Increase of beneficial species	0	10	90	67	23	10	0.000	****
Reduction of invasive alien species	10	17	73	47	47	7	0.000	****
Control of fires	13	7	80	30	30	40	0.000	****
Reduction of dry material (fuel for wildfires)	0	17	83	17	43	40	0.000	****
Promotion of suitable livestock varieties	13	13	73	43	30	27	0.000	****
Increase in livestock diversification	13	10	77	37	33	30	0.000	****
Spatial arrangement and diversification of land use	3	3	93	57	30	13	0.000	****
Controlling water degradation †	**9**	**20**	**71**	**59**	**32**	**9**	**0.000**	****
Increase/maintain water stored in soil	3	13	83	40	47	13	0.000	****
Improvement of harvesting/collection of water (runoff, dew, snow, etc.)	3	13	83	70	23	7	0.000	****
Reduction of evaporation	0	27	74	67	27	7	0.000	****
Increase of groundwater level, recharge of groundwater	37	23	40	77	20	3	0.000	****
Water spreading	3	10	87	40	47	13	0.000	****
Improvement of water quality, buffering/filtering water	7	33	60	63	27	10	0.000	****

ᵠ N = 30, † Mean among the corresponding controlling factors, 1 = Less important/little extent, 2 = Important/medium extent, 3 = Very important/large extent, **** ≤ 0.001.

Annex 10. Differences in mean annual economic inputs for adaptation measures between AFS and CAS (modified based on Table 3 in Study III).

Annual inputs and materials for adaptation	AFS φ	CAS φ	t-Sig. (2-tailed)	Significance
Labour	(# persons)			
Family labour	3	4	0.219	NS
Permanent Family labour	2	1	0.289	NS
Hired labour	1	1	0.770	NS
Labour cost	(USD)			
Permanent family labour	4622	3828	0.317	NS
Hired labour	329	73	0.260	NS
Subtotal labour cost	**4951**	**3901**	**0.212**	**NS**
Equipment cost				
Machine rent	141	196	0.220	NS
Animal traction	4	32	0.098	*
Tools	18	17	0.819	NS
Other equipment [a]	229	144	0.351	NS
Subtotal equipment cost	**392**	**389**	**0.974**	NS
Construction material cost				
Stone	0	0	0	-
Wood	0	22	0.118	NS
Earth	0	0	0	-
Other construction materials †	187	28	0.231	NS
Subtotal construction material cost	**187**	**50**	**0.313**	NS
Agricultural cost				NS
Seeds	49	104	0.187	NS
Seedlings	118	72	0.317	NS
Fertilisers	364	52	0.132	NS
Biocides	43	23	0.285	NS
Compost/Humus/Manure	55	20	0.156	NS
Subtotal agricultural cost	**630**	**271**	**0.104**	NS
Subtotal Other costs ‡	**286**	**889**	**0.006**	***
Total cost	**6446**	**5499**	**0.358**	NS

φ N = 30; * p ≤ 0.1; *** p ≤ 0.01; NS = p ≥ 0.1; - Not applicable; [a] irrigation implements and spares, † wire, barbed wire, greenhouse film, etc. ‡ livestock, minor animals, fodder, vaccines, vitamins, inseminations, etc.

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